Optical Fiber Sensors for Residential Environments

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1. INDEX

Contenido

2. INTRODUCTION: ON THE WHY AND WHY NOT OF OPTICAL SENSORS IN BUILDINGS

The aim of this project is to start creating an awareness, to convey the idea that optical sensor technologies are now technically and economically mature enough to provide safety enhancement features in the residential environment and market. A first application of these technologies can be that of real time building structural health diagnosis: a utility company or telecommunications operator is in a position to provide it as a service by means of its urban optical fiber infrastructure and service management expertise.

There are several advantages accruing from continuously monitoring the structural health of buildings. However, among them there is one that stands up as the overriding driver for the long term measurement of mechanical strain in key points of building structures: the prevention of building collapses and their associated loss of human life, personal injuries and economic damage. This last item falls on the building owners and residents, the companies which insure them, municipal or regional authorities and, in general, society as a whole.

The economic damages arising from the catastrophic destruction of a building can be quantified, as shown in Table 1, where the direct economic loss attached to a building collapse is shown, depending on the degree of collapse.

Table 1 - Direct economic loss relative to building collapse, average valuation

Damage	**Cost per dwelling unit (apartment, flat) square meter (€/m^2)**
Total collapses	850
Great damage (unfeasibility)	550
Medium damage	280
Low damage	150

To this direct cost a social cost has to be added, which in the case of great damages has been evaluated at 350 €/m^2. At this level of damage the total cost per dwelling unit square meter then turns out to be 550 + 350 = 900 €/m^2 .

To prevent these losses and damages, as well as the social and sometimes political alarm derived from them, in many European cities it is now compulsory to perform periodic building inspections. In countries with seismic risk additional measures are taken; in Italy, for example, all buildings require a “log book”, where all factors affecting the building status have to be recorded.

From this rationale, this work proposes the use of optical fibre strain sensors attached or embedded in building structures to monitor their health. Optical sensors have for years, now a few decades, been carving themselves a niche in the industry arena. Acoustic, electric field, temperature and strain sensors are now used in military submarine listening arrays, power transformer installations, high current cables and bridge spans, to name but a few applications, and usually as a better alternative to older, far more established sensing devices. The reasons for it are usually not that they are more sensitive than their older counterparts, but that they share the inherent advantages of optical fibre over metallic conductors, namely, their insensitivity to corrosion and electromagnetic disturbances and, especially, that they do not require electrical feeding, with its associated connecting metallic conductors, which are heavier, bulkier and subject to corrosion.

However, the fact remains that, though they work and work well, optical sensors are still confined to high end industrial and military applications, and have not entered any mass market. The reason for it is also well known: they and their associated measurement equipment are more expensive than metal based sensors and equipment, respectively, and for short distances to the measurement equipment copper cabling is cheaper than fibre.

This broad and simple picture is good enough to explain a general situation. But finer detail and a greater understanding are required to move forward and progress. Research carried out within this project has shown that there is a latent demand for a new service, that of long term structural monitoring of buildings, i.e., the long term measurement of mechanical strain in building structures. And, like in any other service, there are some user requirements attached to it, besides a low enough price, which necessarily have to be met if the service is to have a chance of being accepted, or even of being considered for acceptance.

The how much the service would cost, who would be willing to pay for it and under what circumstances, what installations it requires and how they would be run, and other related issues will be addressed throughout this document. What will be explained in the next paragraphs is that for this application optical sensors are a good choice, and that the natural building strain measurement service provider is a telecommunications operator or a utility company.

If mechanical strain is to be measured in a building structure the classical way to proceed is to place so called strain gauges, which are inexpensive, at identified key points in the structure. Afterwards, copper pairs have to be installed to connect the gauges to a measurement equipment set, four to each sensor, which electrically feeds and interrogates them. Finally, the equipment has to be connected to a telephone or data line, which regularly reports the measured data to a remote management center. In fact, from this description it emerges that strain measurement can be another feature of a domotic home.

The first snag appears with the measurement equipment. It is expensive, more than six thousand euros for a set of ten sensors, when a building will most likely require twenty or more. And it is based on long standing established technology, which makes it unlikely that its price will go down substantially. And it has to be housed in the building, or very close to it, because the ohmic losses in the -many required- copper cables do not allow for remote connections.

The second snag follows the first one. The in-building measurement equipment has to be serviced over the years, even, or especially, if the building is vacant. This involves powering, maintenance and software upgrades, which somebody has to implement.

Optical sensors revolutionize this picture. One single optical fibre reaching an area can monitor hundreds of sensors, distributed over several buildings or even a building block. The sensors are not powered, and the measurement equipment can be kilometers away, continuously polling tens of fibers, or hundreds of buildings, in which the building tenants are not even aware that the building structure is being looked after. And these fibres can be shared with other telecommunications services, by means of wavelength division multiplexing. An attractive candidate for providing this service is then a telecommunications operator, or utility company, which already deploys urban optical fibre infrastructure and owns sites throughout their service area where centralized measurement sets can easily be installed and managed.

The coming chapters describe this optical strain measurement system, its architectural considerations, its cost in different business scenarios, and the results of some in house demonstration tests. The reasonings behind the choices made between different alternatives in the system concept are also explained.

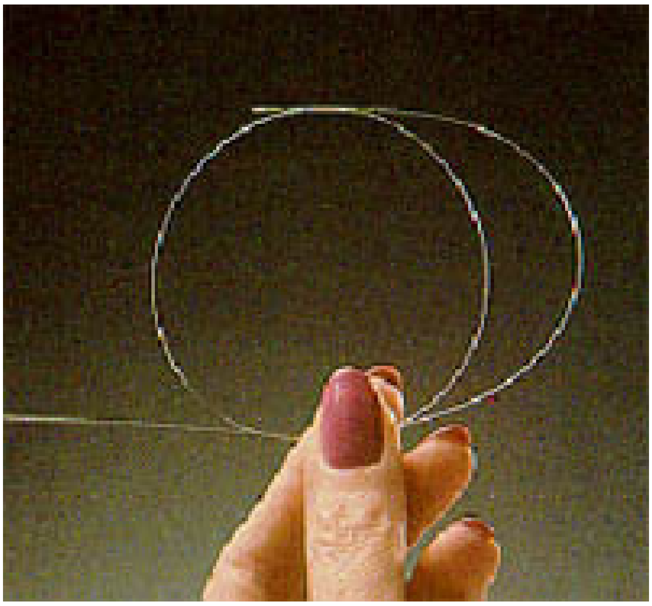
2.1. ACRONYMS

FBG:	Fibre Bragg Grating
FWHM:	Full Width Half Maximum
FSK:	Frequency Shift Keying
nm:	Nanometer
OTDR:	Optical Time Domain Reflectometry
λ:	Symbol for wavelength
PON:	Passive Optical Network
pm:	Picometer
SOA:	Semiconductor Optical Amplifier
SNR:	Signal to Noise Ratio
$\mu\varepsilon$:	microstrain
WDM:	Wavelength Division Multiplexing

3. THE OPTICAL STRAIN SENSOR

The strain sensor, or strain transducer, is a fibre device known as Fibre Bragg Grating (FBG). Seen from outside, as shown in Figure 1, it is just a piece of optical fibre; in fact it is a piece of optical fibre a few centimeters long, along which a periodic variation in its refraction index has been fabricated by exposing the fibre to an ultraviolet light pattern. The index variation period is nominally one half the wavelength of the light propagating in the fibre. In reality, this period is suitably modulated by design so that the FBG achieves the working characteristics sought by the designer.

Figure 1 – Photograph of unpackaged FBF strain sensor



In its simpler version the FBG acts as a wavelength selective mirror: at a certain wavelength, called the resonance wavelength, the light propagating along the fibre is reflected when reaching the FBG. Under a more complex index variation design the FBG shows not just a reflection at a single wavelength, but a reflection which varies in intensity as a function of wavelength following a predetermined reflectivity function.

The strain sensing property of the FBG stems from the fact that its reflectivity function shifts linearly in wavelength with the mechanical strain applied to it. So, if the FBG, or at least its ends, are cemented to an expanding surface, as the surface expands, or strains, the FBG resonance shifts. If under normal conditions the FBG is prestrained, its index of refraction also shifts with wavelength in the opposite direction when the surface contracts.

In Figure 2 the resonance frequency shift of some FBGs fabricated and employed in this project is shown. The measured strain coefficient is:

$$\textit{strain coefficient} = 1.12 \pm 0.01\ pm/\mu\varepsilon$$

where the strain unit, the microstrain, με, is a length variation of one micrometer per meter of length. Also, at a central wavelength of 1540 nm a wavelength shift of 1 pm, one picometer, is equivalent to a frequency shift of -126 MHz, or -0.126 GHz. In general, and depending on the fibre type and FBG fabrication procedure, strain coefficients lie in the range of 1-2 pm/με.

From these facts it follows that the strain a structure is undergoing can be calculated by measuring the resonance wavelength shift of an FBG attached, cemented, to it.

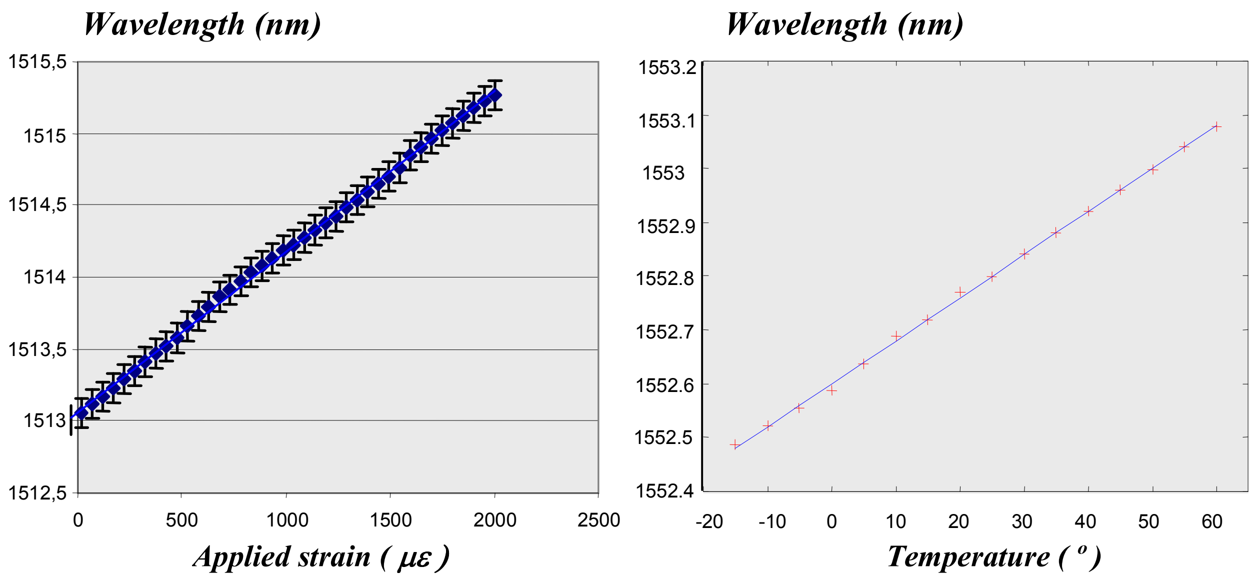
The FBG resonance wavelength also shifts with temperature. For the fabricated FBGs the shift is shown also in Figure 2, and the temperature coefficient turns out to be:

$$\textit{temperature coefficient} = 8.12 \pm 0.06\ pm/^{o}C$$

It is then obvious that when measuring the sensors resonance wavelength shift some way has to be found to remove from the measurement the temperature variation effect, whose associated wavelength shift masks that due to strain.

There is far more to be said about the FBG sensors, like their most suitable reflectivity and associated index of refraction functions, eventual problems due to aging and the way to circumvent them, procedure to order them from commercial vendors, etc. These items, and some others, are dealt with in Annex C.

Figure 2– FBG resonance wavelength shift with applied strain (left) and temperature (right)



4. THE ARCHITECTURAL CONSIDERATIONS

Architectural considerations answer the following questions: how much strain has to be measured and where in a building should the strain sensors be placed, and how many?

As derived from architectural known data, in medium sized apartment buildings strain values of 100 microstrains (100 με) can be expected under normal conditions. However, it is not for reporting normal conditions that the sensors are sought, but for detecting conditions which are not normal, but potentially dangerous. Depending on the building, strain can reach values of 500, or even 1000, με. Indeed, the strain measurement system should activate an alarm warning when these values are reached. Temperature also has to be taken into account: ambient temperature values can range from -20º to +50º (Celsius), with temperature differences between different sensors of up to perhaps 60º, in an extreme case.

The sensors should be placed in the so called "crisis points", which in colloquial language can be understood as the places where cracks were first appear if the strain were too high, as can be seen in Figure 3.

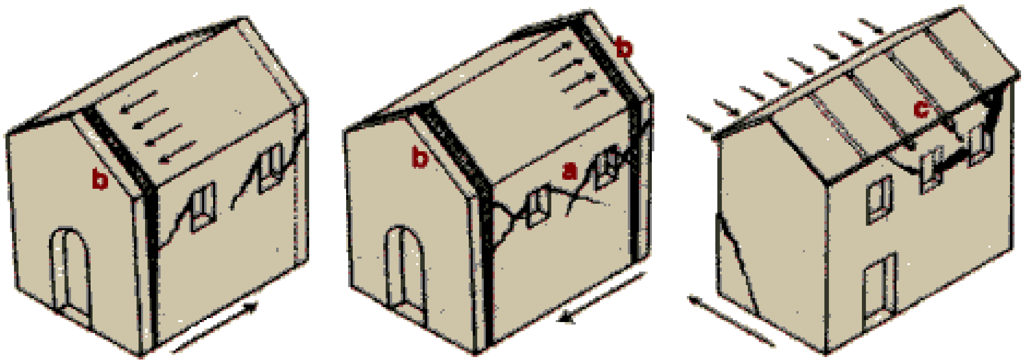
Figure 3 – Examples of cracks in buildings

In reinforced concrete structures, the great damages in case of structural troubles are in knots, in the corner pillars and in the "brick wall" near the openings.

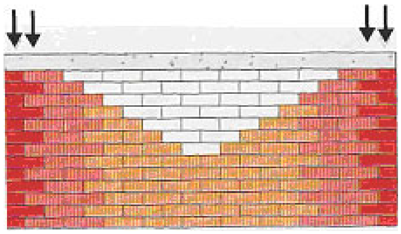
The location of crisis points depends on the building and the building typoloy. In this work two types of buildings have been addressed, as representative of a large percentage of buildings in Europe: those based on load carrying walls and those based on load carrying pillars. Figure 4 and Figure 5 refer to these two building typologies, respectively.

Figure 4- Typical breaks verified in a concrete building caused by seismic impact waves.

Cut damages, or “S. Andrew crosses” (a), damages caused by detachments in orthogonal concrete walls (b) and wall corner lesions caused by coverings beams for a punching effect (c)



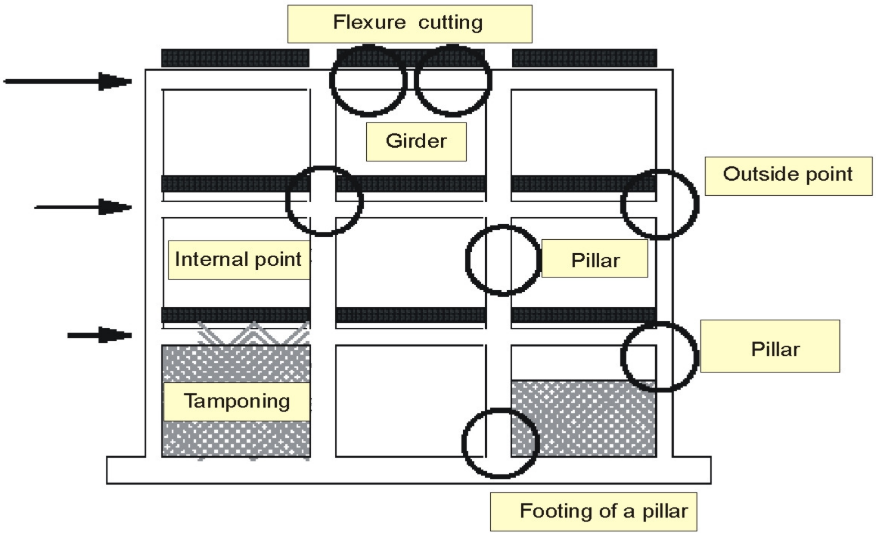
The collapse in a carrying wall building takes place instantly, and is hardly controllable



Resistance Scheme in a wall structure

Red	***elevated resistance***
Orange	***medium resistance***
Yellow	***low resistance***

Figure 5 – Typical structural problems in reinforced concrete frames in load carrying buildings

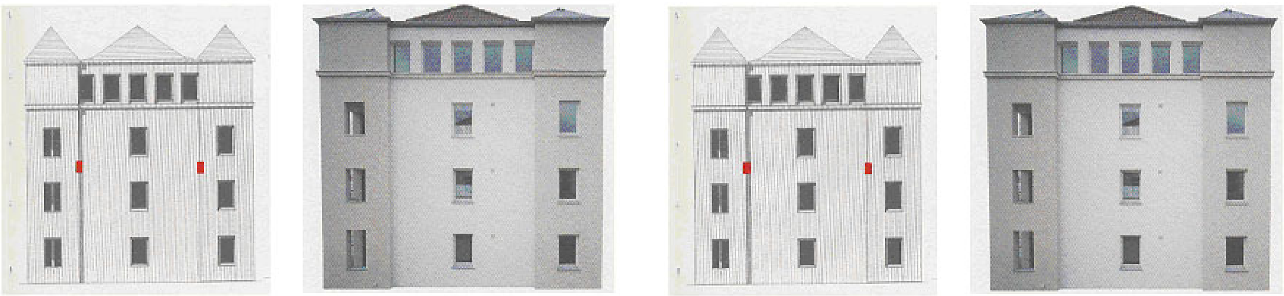


Structural typical problems of frames in reinforced concrete

In Figure 6, the (crisis) points where sensors should be placed in a medium sized building are shown as a representative example for the two selected building typologies: load carrying walls and load carrying pillars. The number of points in both buildings is the same, 20, but it is worth remarking that although some points are identical, others are subtly different.

Figure 6 - Proposed sensor placement points in carrying wall (left) and carrying pillar building (right) building

Front A Front B Front A Front B



Front C - D Front C - D

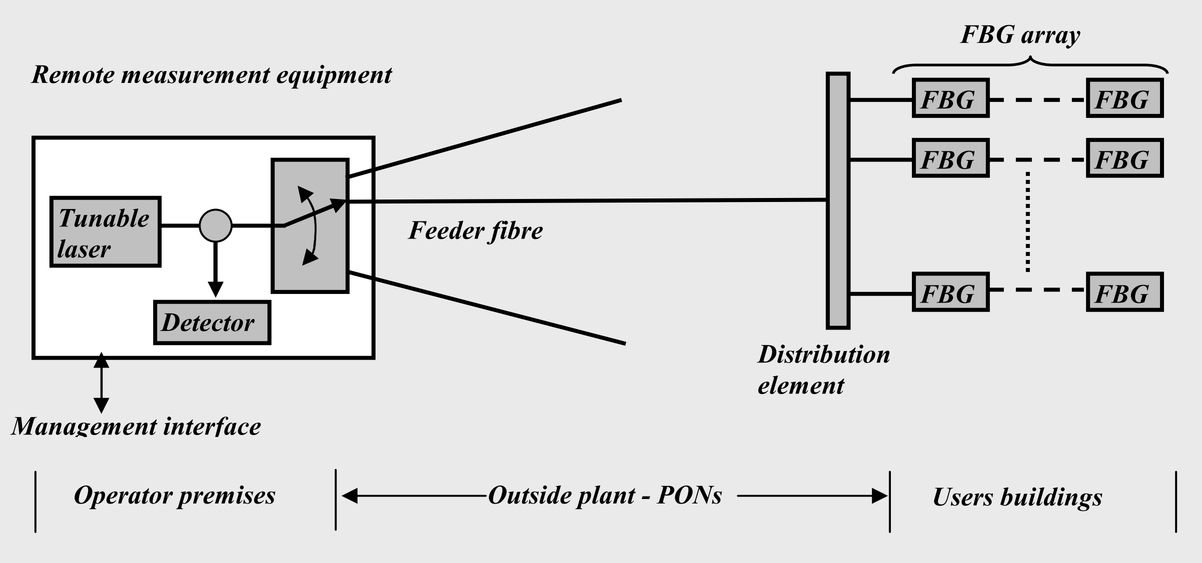
5. THE CONNECTION OF SENSORS: SENSOR NETWORKING

From an overall system point of view it can be stated that how the sensors are connected is at least as important as the sensors themselves: acceptability of the whole strain measurement scenario is dependent, among other factors, on the possibility of servicing a large number of sensors from a remote surveillance center with a small number of outside plant optical fibres. Outside plant can be understood as “out on the street”, or “under it”.

In Figure 7 the reference configuration for the measurement system is shown, including the way the sensors are connected among them and with other elements. The figure has been kept deliberately simple, for ease of understanding, omitting supporting elements which are later described. A more detailed configuration is shown in a subsequent section. The following main parts can be identified:

- Remote measurement equipment, in the operator or utility premises
- Outside plant, made of feeder fibres and distribution elements
- FBG sensors, embedded in the users buildings
- Interface to an external management system

Figure 7 - Definition of terms in the structural strain measurement system



The basic system description is as follows. In a site, belonging to the provider of the structural strain measurement service, centralized measurement equipment is housed. The measurement equipment is basically a tunable laser and an optical detector, with an associated electrooptical receiver and control unit. The laser launches suitably wavelength scanned optical signals into a feeder fibre which exits the site and reaches the remote set of buildings, or building block, where strain is to be measured. The fibre belongs to an optical outside plant made of fibre cables and connection elements placed in ducts and distribution boxes.

In the buildings the FBG sensors are placed in the crisis points identified by an architectural analysis, and are deployed as arrays: each array consists of a number of sensors, up to around fifteen, series connected by means of a single optical fibre, as is shown in Figure 7. Each array is laid along a part of the building structure, as is described in a later paragraph, with up to six arrays per building, perhaps more, depending on the building size and characteristics.

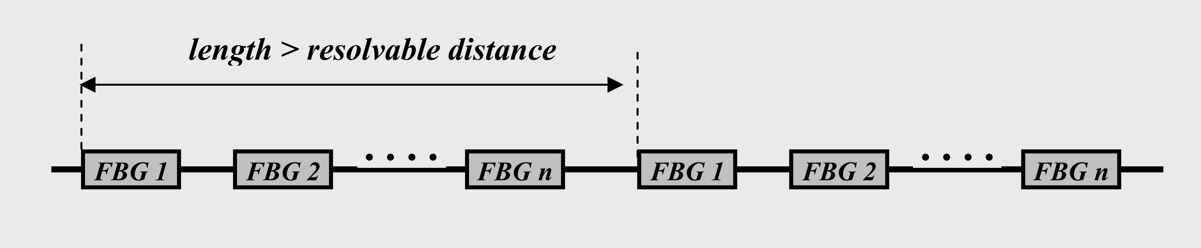
There are two features about the sensor arrays which are worth highlighting:

1. All arrays are basically equal, with just the fibre span lengths between FBGs being different. The nominal resonance frequency of the i_{th} FBG in any array is equal to that of any other array´s i_{th} FBG, to simplify the manufacturing, inventory and system management processes

2. In one same array the different FBGs have the same reflectivity function shape, but are all centered around different resonance wavelengths. The nominal resonance wavelengths are regularly and sufficiently spaced so that within the expected strain and temperature range of operation they do not overlap, and the measurement equipment is capable of resolving all FBGs.

   If the number of different wavelengths which fit within one array is too low, as might be the case if very high values of strain are expected (see Annex C.2), it is always possible to have the arrays with twice the number of FBGs, by having first a subset with all the available wavelengths followed by another equal subset. The only provision in this case is that the fibre distance between the first FBGs of both subset be larger than the system resolvable distance. This concatenation is shown in Figure 8.

Figure 8 – Allowable repetition of wavelengths along one array



Each feeder fibre is connected to several arrays by means of an optical splitter. A number of technical and standardization factors recommend that in an actual deployment the number of splitter ports be 32, i.e., that each feeder fibre be connected to up to 32 FBG arrays.

As can be seen, all outside plant elements and the FBG arrays are passive, allowing their ensemble to be considered as a Passive Optical Network, or PON, a well know term in the telecommunications industry.

At this stage, to be able to proceed with the system description in a way which is easily understood it is first necessary to make a break to explain how the measurement process works, and what requirements it places on the sensor deployment.

5.1. DESCRIPTION OF THE MEASUREMENT SYSTEM: PRINCIPLE OF OPERATION

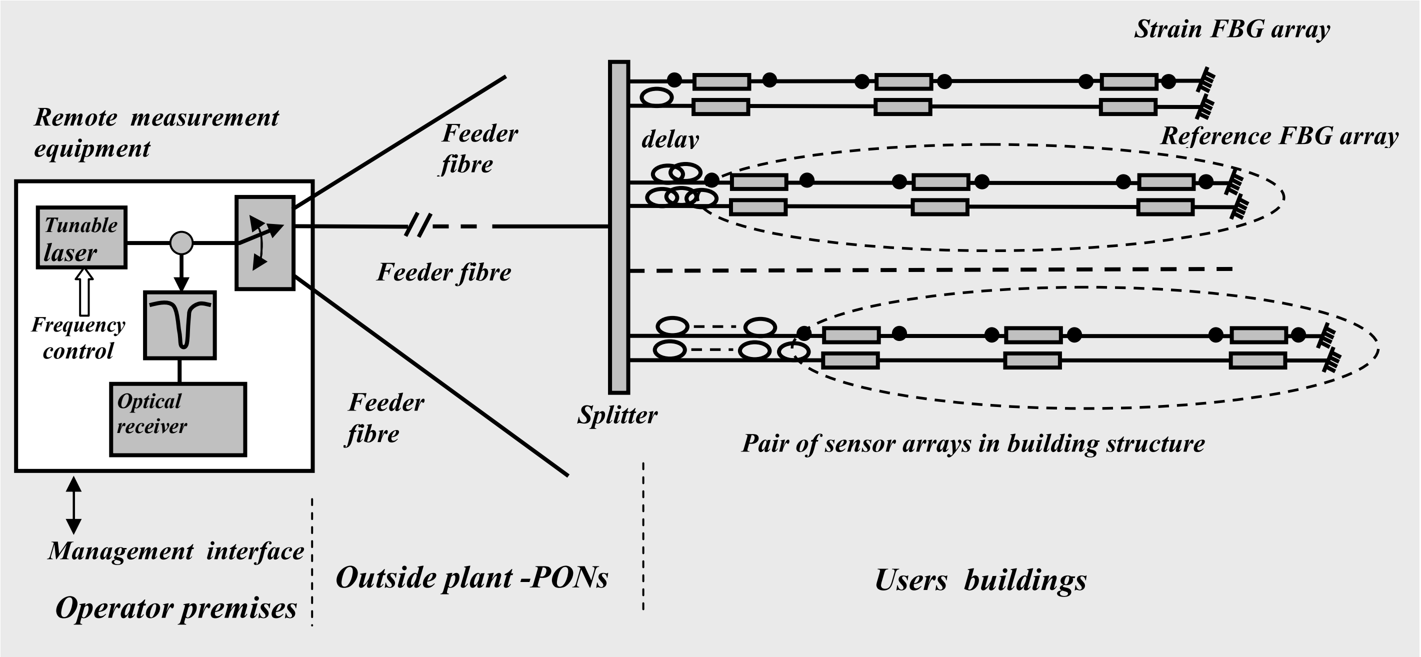
As was mentioned earlier, an FBG resonance wavelength shifts with the mechanical strain it is subject to. So, if the FBG is cemented to a structure, it is possible to calculate its strain by measuring the FBG resonance wavelength, the wavelength at which it reflects the light impinging on it along its connecting optical fibre.

Basically, the way to measure the strain is to launch into the fibre optical pulses at different wavelengths, and to measure the reflections coming back from the FBG. Since only the pulses whose wavelength matches the FBG resonance are reflected, by keeping track of the reflected pulses the resonance wavelength is determined, and from it the strain.

In the measurement system shown in Figure 7, the wavelength encoded optical pulses are generated at the tunable laser, propagate along the feeder fibre and break into up to 32 equal replicas at the splitter. Since all arrays are nominally equal, it is very probable that several FBGs reflect at the same wavelength. When that happens, for each pulse there are several reflections which combine at the splitter and arrive together at the detector, whose associated control circuitry has somehow to resolve them, and to determine what is reflecting from where.

To understand how this is achieved, it is now necessary to leave the simple system description from Figure 7 and turn to a more comprehensive one, which is shown in Figure 9.

Figure 9 - Overall strain measurement system



As can be deduced from Figure 9, even though all arrays are nominally equal, their distance to the splitter is different. From each array to the splitter there is a fibre section, and the lengths of these sections are all different. In Figure 9 the sections are marked with the term “delay”, since their purpose is to force a differential delay between all reflections impinging back on the splitter at a same wavelength.

So, the way to identify at the optical receiver which reflection is coming from which FBG is to make use of the fact that FBGs resonating at the same wavelength are placed at different distances to the measurement equipment; in short, what has to be done is to resolve distances. The standard method to resolve distance, the so called Optical Time Domain Reflectometry, OTDR, consists on sending along the fibre short optical pulses, and measuring the time it takes for their reflections to reach the measurement equipment receiver. In this way, both the position and intensity of the reflections along the optical fibres can be determined. And, as has been stressed, it is also required that each pulse has a different wavelength.

At this moment an additional drawback turns up. For the tunable laser used in this project, in fact for all tunable lasers applicable to this measurement principle of operation, the procedure of turning on and off the laser output to generate pulses at different and precisely determined wavelengths is, regretably, unfeasible, because when the laser is turned on it takes a few seconds for its wavelength to stabilize, whereas the pulse duration should be no longer than a few hundred nanoseconds.

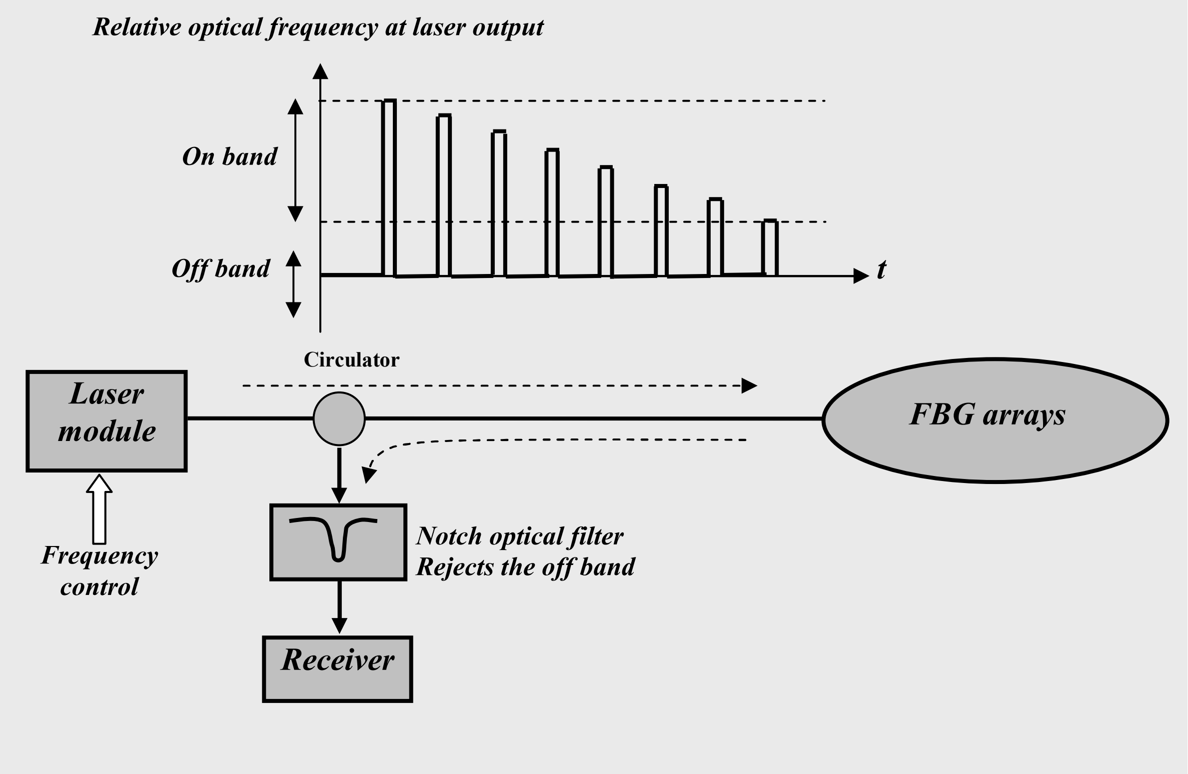
One alternative procedure equivalent to turning the laser on and off, which is feasible with the kind of state of the art tunable lasers recommended by this project, is to take advantage of the lasers fast wavelength switching speed (tens of ns). It is shown schematically in Figure 10. Its principle of operation is to divide the optical wavelength space in two bands: the first one, or "on band", contains the Bragg gratings´ resonance frequencies, and the second one, "off band", is empty of them. The laser addresses the gratings not with optical intensity pulses, but with pulses in the wavelength domain, i.e. short periods of time with output in the "on band", followed by longer periods, which will be termed "off periods", during which the frequency is in the "off band". The receiver is preceded by a band reject, or notch, filter which eliminates the "off band". Thus, it is reached by reflected optical pulses which are identical to those which would be received if the laser could be really turned off during its "off period". The notch filter is readily implemented with a Bragg grating, whose key parameters to be specified are its reject band and insertion losses. This measurement procedure, or interrogation strategy, will be termed Frequency Shift Keying (FSK) OTDR, since the frequency, or wavelength, both terms are equivalent, is modulated, keyed, in discrete steps.

To determine the maximum pulse duration in the “on band”, let´s assume that a space resolution, Δl, of 20 m is acceptable. If the arrays are numbered by their distance to the splitter along the fibre, or optical distance to the splitter, the minimum difference in distance to the splitter between two consecutive arrays must be larger than the space resolution. Since the pulse duration, Δt , should be smaller than the pulse roundtrip time, it follows that:

$$\Delta t \quad \leq \quad \frac{2 \cdot \Delta l}{c} \cdot n \qquad \textbf{(Eq. 1)}$$

where $c = 3 \cdot 10^8$ m/s is the speed of light and $n = 1.44$ is the fibre index of refraction. For $\Delta l = 20$ m, $\Delta t < 192$ ns.

Figure 10 - Measurement system OTDR operation (FSK-OTDR)



The pulse duration in the "off band" is also simple to calculate, since it has to be longer than the overall network roundtrip time, which is readily calculated as 9.6 μs per kilometer. So, if the distance from the farthest FBG to the measurement equipment is L km, the "off band" pulse duration has to be longer than L x 9.6 μs.

So far, what the system achieves is a measurement of the resonance wavelength. What then has to be determined is how much this wavelength has shifted from its original pre-strain, and how the effect of temperature on wavelength is removed. For that it is necessary to implement what in this project is called "sensor referencing".

5.2. SENSOR REFERENCING

In FBGs the shift due to temperature variations is comparable, or even larger, than that due to strain. To prevent temperature from masking strain it is necessary to deploy the gratings in pairs, one subject to strain, the strain grating, and the other not subject to it, the reference grating, but in close proximity to the strain one, so that both of them are at the same temperature. The two gratings are identical. In this way, strain values can be calculated as the difference in resonance wavelength shift between the strain and reference gratings. This scheme is represented in Figure 11.

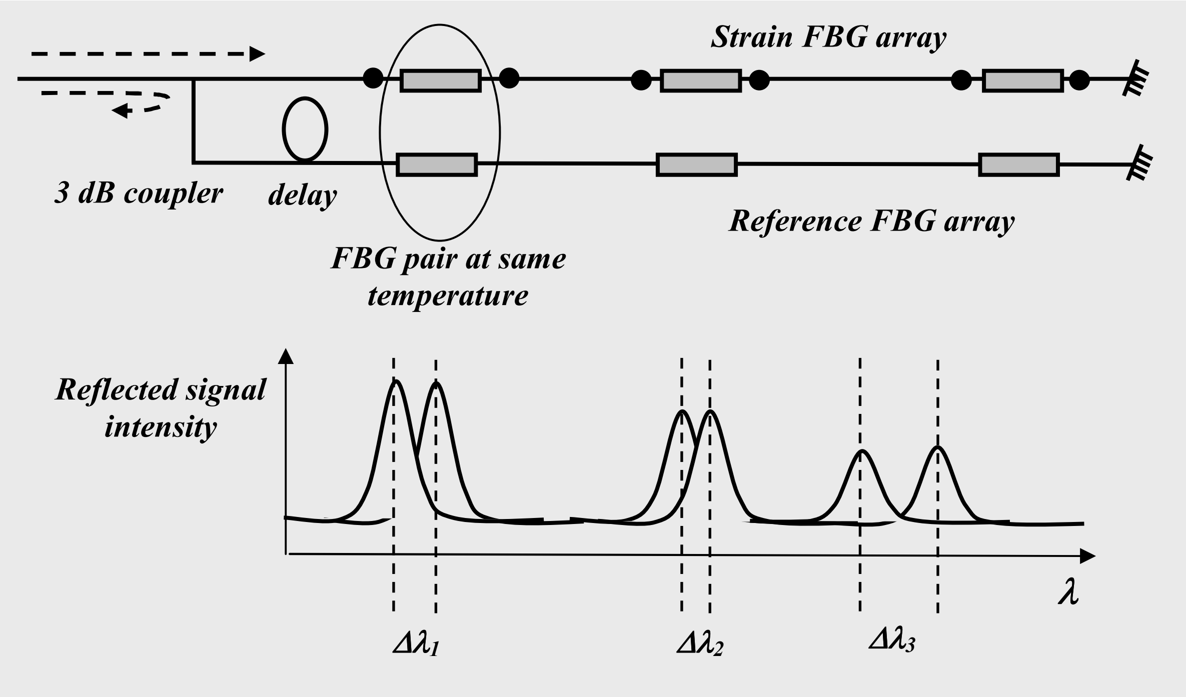
In Figure 11 the strain sensor is depicted with its two ends cemented to the structure, so that its strain is transmitted to the sensor, while the reference one is loose, without strain. The two sensors are optically connected to the incoming fibre through an optical tap, i.e., a 3 dB coupler. To avoid interferometric effects between the two reflections, their distance to the splitter is made longer than the OTDR resolvable distance by means of a delay fibre section, i.e. a piece of fibre longer than the OTDR resolution. In this way, as the wavelength of the "on band" optical pulses is swept, the reflected signals produce a double peak at each FBG pair, as shown schematically in Figure 11. Since the two FBGs are at the same temperature, the wavelength difference between the reflection peaks translates into a direct reading of the strain difference between the two FBGs. In Figure 11 it is also shown in an exaggerated way that as light propagates along the fibre and traverses different FBGs, its intensity diminishes.

Though in Figure 11 the referencing procedure is shown for one array pair, it is easily generalized to several pairs by replacing the 3 dB coupler by a multiarm splitter, with its delays, as shown in Figure 9. It can be seen that the splitter ports are grouped in pairs,one port of the pair for a strain FBG array and the other for the reference one. It is obvious, then, that the actual number of strain measurement points is one half the number of deployed sensors. The referencing procedure is certainly powerful, but for it the price of reducing the system measurement capacity by one half has to be paid.

The use of sensor referencing brings another advantage to the measurement system: because referencing involves a differential measurement of wavelength shifts, the tunable laser baseline wavelength error, or wavelength inaccuracy, is removed when measuring strain. On the other hand, if the system were to be used for measuring not only strain, but also temperature induced wavelength shifts, which are common to the reference and strain sensors, the laser wavelength error translates directly into a temperature reading offset.

As a last comment to the elements shown in Figure 9 and Figure 11, the fibres on which the arrays are fabricated have to be ended on an absorbing termination, so that no unwanted reflections which could lead to interference are generated at the fibres´end.

Figure 11 - FBG sensor array referencing



5.3. ENDING THE SYSTEM DESCRIPTION: OPERATION AND SERVICE

It is now possible to end the system description adding some further facts to the information already furnished on the measurement equipment.

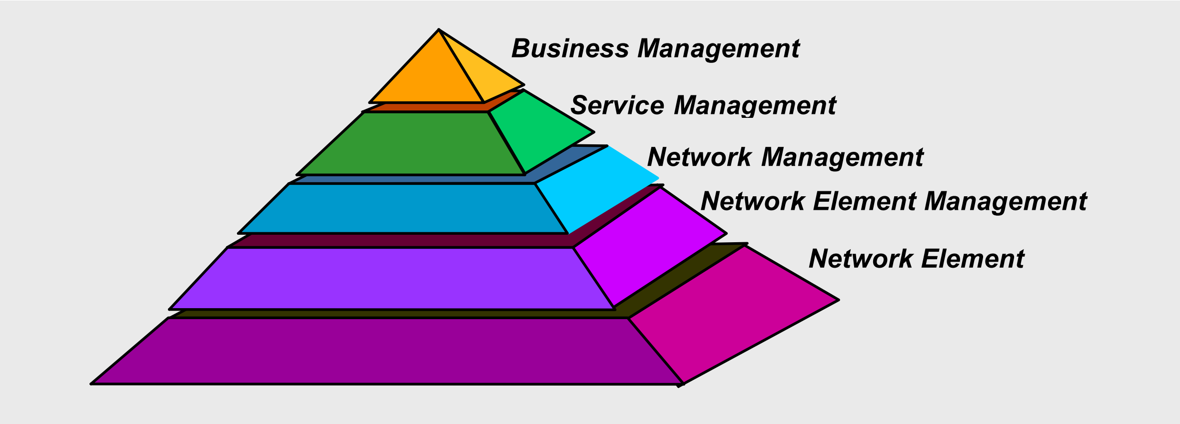
The measurement equipment includes an optical transmitter, which is basically a fast tunable laser, an optical receiver with an accompanying band reject filter and a fiber selector, or switch. The selector allows the equipment to be sequentially connected not to one single feeder fibre, but actually to a large number of them, currently fifty or more. This means that the cost of one single measurement equipment set can be shared by at least fifty PONs. Since it has been estimated that an average middle sized building requires four to six arrays –more on this later-, arranged as two or three pairs, one feeder fibre could service at least five different buildings, and one equipment set five times fifteen, 250 buildings. As this implies, and will be commented later, this sharing capability means that the measurement equipment impact on the overall system cost is irrelevant.

The most demanding item in the measurement equipment is the fast tunable laser, which within a predefined wavelength channeling, like 50 GHz, has to be able to jump between any two channels in less than 100 ns. Details about this laser can be found in ANNEX B.

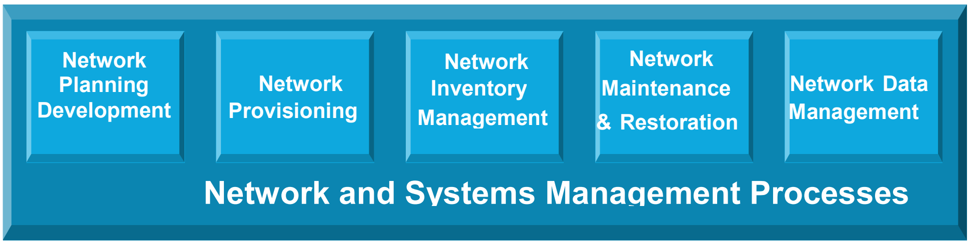
The tunable laser requires some controlling hardware and software for programming its tuning procedures. Also, the receiver circuitry provides wavelength data which have to be translated into useful strain information and reported to an outside information system. This means that the measurement equipment has to be provided with a management interface, which connects the equipment with an external management system, which in turn manages all the measurement systems the service provider is in charge of in one or several towns or cities.

The management system should not differ significantly from other ones routinely employed for the monitoring of data gathering systems. In this sense, the traditional management system model can be followed:

Figure 12 – Management system model



Concentrating on the network layer, the following main modules can be adopted:



Its detailed description falls out of the scope of this document. Here it will just be mentioned that it must cover, as a minimum, the following functional areas:

- Network Planning and Development - The management system must be able to:
  - Add or delete from the management system new measurement sites, and for each site detail the location of each measurement point, i.e., building address and place within the building.
  - Cluster groups of buildings in sub networks, to provide the operator with graphically attractive geographical information.

- Network Inventory Management - For each measurement site, store the parameters that describe every PON connected to it.

- Network Maintenance & Restoration

  Whenever a strain threshold level is reached or passed, the management system generates an alarm which informs the system operator of the building where the threshold has been breached. Further studies nonwithstanding, this threshold level is provisionally established at 1000 $\mu\varepsilon$.

  Typical functions to be covered are:

  - Program the measurement characteristics of each measurement equipment set, i.e., period of reporting, number of measurement repetitions per measurement point, etc.
  - Program the quiescent strain levels
  - Adjust the alarm threshold levels

  Performance is inherent to the measurement system. For each measurement point, the measurement system periodically sends to the management system the measured resonance wavelength of both reference and strain sensors, from which the system determines the strain at the point.

  Irrespective of the measurement time, the system will store only average strain values, measured during periods of predetermined length, as well as peak variations during the period. Under normal operating conditions, the period length shall be measured in days. However, the operator will be capable of requesting shorter averaging periods, to monitor, for example, possible strain variations during the duration of nearby public works.

The summary description of the management system serves as a stepping stone for recommending the sort of company which should be best suitable for providing the strain measurement service, or, more properly speaking, the remote supervision of strain measurement in building structures. It should have the capability of reaching thousands of building premises, laying or reusing outside plant optical fibre, managing tens of thousands of distributed elements and capable of committing itself to multiyear measurement programmes, with their associated data processing and storage. These attributes almost define an utility company, with a preference to a telecommunications operator, because of the commonalities of running the optical operations with those of broadband access networks.

6. THE BUSINESS

The business which can spring from the remote monitoring of structural integrity in buildings by means of passive optical sensors, from here on the service, can be defined as the set of the following entities:

- Client
- Service provider
- Boundary conditions, which include regulation and cost sharing
- Cost, to the service provider, which can use it as a variable for determining the price

The service provider by excellence is a network operator, as has been reasoned in a previous section, with a utility provider coming out as second option. As for the client, in principle there are three options:

a) The building owner
b) The building insurance company
c) The municipal or regional authority

As a rule, the first option can be discarded: it is unlikely that in today´s social environment a building owner is going to spend any amount of money on the building structural monitoring, unless forced to do so by law. However, this does not rule out that under special circumstances some owners would be willing to do so.

Insurance companies are more likely to pay for this service, provided the payment translates into a corresponding decrease in damage awards. This might be the case not everywhere, but in areas with a certain seismic risk, or in metropolitan areas where it is recognized that public works or high vibration levels due to ground transportation systems pose a risk of ground subsidence or structural degradation. Even so, the companies would not embark on this business unless some other entity did so first, demonstrating the service usefulness.

These other entities are the municipal or regional authorities, who bear a large share of the responsibility of buildings and public safety. Properly advertised, the service introduction could also provide the authorities with additional returns in terms of public welfare or political recognition.

The final and most important item is the cost, which in turn depends on the underlying assumptions or boundary conditions. These are mainly of two types: degree of utilization of the service, or service penetration, and degree of sharing of the outside plant infrastructure with other services.

This last item requires some clarification. The feeder fibre might be used exclusively for the service, but it can also be used for other telecommunication services, by means of wavelength division multiplexing (WDM). In fact, not to use this possibility in urban environments can be considered a waste, considering the high price which is usually charged for dark fibre rental. And if the fibre is shared, so can the fibre cost.

These assumptions form the basis for several business scenarios, with varying degrees of service penetration and fibre infrastructure sharing.

There is one remaining item in the cost evaluation, that of the sensors installation in buildings. It is assumed that these sensors and their cabling belong to the building owner, and do not take part in the service offering. Their cost is addressed in 0, but here it can be stated that in new buildings it is negligible when compared to the building price, and that in building renovations their cost is equivalent to that of changing the plumbing. There is a third possibility, that of buildings made of prefabricated structures, which is the most advantageous of all from a cost point of view.

6.1. BUSINESS SCENARIOS: MARKETS AND ARCHITECTURE OPTIONS

Four different markets have been studied. They are the following

A. Big city / Exclusive Use

In this case the system is deployed in big cities and is used to monitor structural strain in special buildings or constructions, like museums, bridges, public halls, etc.

B. Big City/Intensive Use

The system is deployed also in big cities, but differs from the previous one in that it is used for monitoring strain in residential buildings, and in special buildings as well, if required. Clearly, the number of customers or clients in this scenario is far larger than in the "exclusive use" case.

Since the difference between intensive and exclusive lies in the number of customers a given measurement system serves, it can also be stated that scenario A can also be understood as covering the residential sector with a low penetration.

C. Small city/Exclusive Use - As in A, but applying to small cities.

D. Small City/Intensive Use - Same as B, but for small cities.

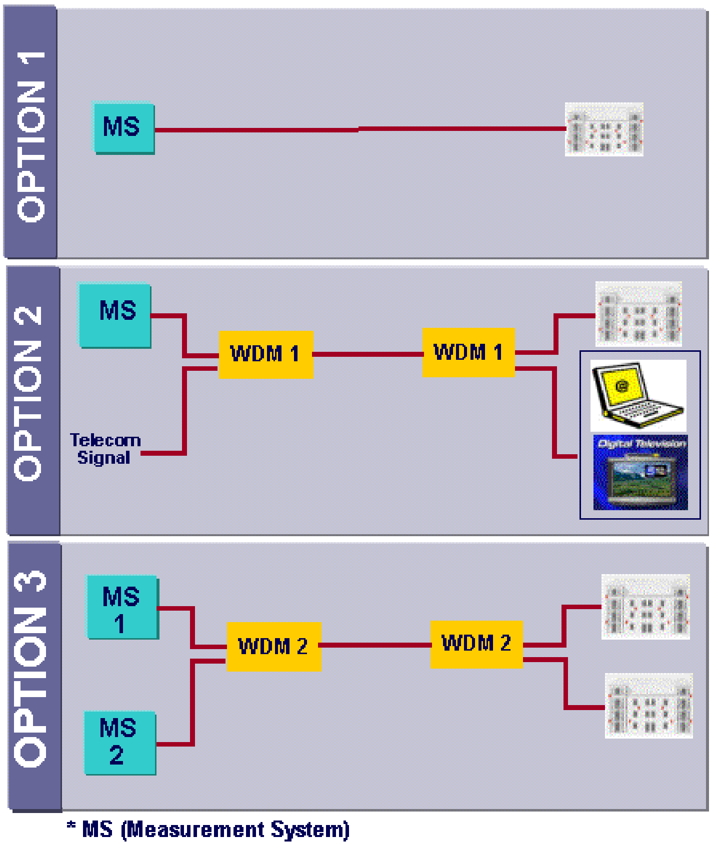
In numerical terms, these four markets are characterized by the the number of different PONs connected to a same measurement equipment set through an optical selector and the number of sensor arrays connected to one feeder fibre in a PON. In this way:

- Big city: the average number of PONs per equipment set is around 40
- Small city: the average number of PONs per equipment set is around 15
- Exclusive use: the average number of used splitter ports per PON is around 10
- Intensive use: the average number of used splitter ports per PON is around 28

In addition, for each one of these markets, different options of the basic measurement system architecture can be applied. In our analysis they differ because each uses different types of wavelength division multiplexers to increase in different ways the capacity of the optical outside plant. The main aim of using them is to achiveve a cost reduction of the final service.

The system architecture options which have been addressed are represented in a schematic way in Figure 13. They are the following:

Figure 13 - Architecture options



1. Basic Use

   In this case the feeder fibre is used exclusively for the measurement system. Correspondingly, all the incurred costs related to the fibre are assigned to the provision of the service.

2. Shared Services

   In this option the capacity of the feeder fibre is used for the provision of the measurement system and for the provision of other telecommunications services, like digital TV or internet access, through the use of WDM techniques (installation of 1300 nm / C Band WDMs). The 1300 nm band is used for the other telecommunication services, and the C band for the measurement system. It can be observed that the use of multiplexers boils down to breaking the fibre optical spectrum into bands, and assigning each band to a service.

   The fibre related costs are in this option charged in the following way: 25% to the strain measurement service and 75% to other telecomunication services. This is a conservative assumption: given the fact that telecommunication services are far more time sensitive than the strain measurement one, an operator could very well charge to them 95% of the fibre costs.

3. Duplicate Use

In this option the capacity of the feeder fibre is used for two different measurement systems operating in the C and L bands, respectively. This case is equivalent to duplicating the feeder fibre capacity of the Basic Use configuration.

The duplication of the measurement system is required because it is not possible today to commercially acquire one which can operate in the two bands. And even if it does appear in the market, it would still be necessary to split the optical signal in two bands at the user end, because each sensor array should not incorporate the very high number of sensors which would be available by combining the two bands, because of their unacceptably high insertion losses.

6.2. SERVICE INFRASTRUCTURE CAPACITY

As has been described in a previous section, from the point of view of infrastructure rollout, the system is a Passive Optical Network (PON) in urban environments. In Figure 14 its infrastructure scheme is represented. It is possible to divide it in three principal caps: remote equipment, PON and connection to the building. Its main characteristics are:

- The PON distribution element is a 32-branch splitter. Each splitter arm is connected to an array of fibre Bragg gratings. Arrays and their splitter arms are always deployed in pairs, one for actual measurements and another for referencing.

- Today, one single set of centralised measurement equipment can reasonably monitor 50 PONs, each PON connected to up to 5 different residential buildings, with between 4 and 6 arrays per building, bundled into 2 to 3 array pairs.This number of arrays includes a provision for failure in one array. The average number of dwelling units, apartments, flats or condos, per residential building is estimated as 12.

- The measurement equipment is basically a fast tunable laser, FSK modulated by short pulses, an optical receiver and a processing section. All these elements provide one single outside control interface through which the equipment is connected to an external management system.

From these data the service capacity, defined as the maximum number of dwelling units one single equipment set can address on one single feeder fibre, basic set option, can be calculated. The calculation is shown in Figure 15, and equals 3.200 dwelling units.