Approaching the Cosmic Speed Limit:

Introducing Hollow Core Fibers for Low Latency and High Capacity

A Technical Paper prepared for SCTE by

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1. Introduction

Folks already know that the speed limit in the Universe is the Speed of Light … nothing is faster. However, many will be surprised to know that light travels slower in an optical fiber than it does in free space! Due to light-matter interaction, the speed of light, which is about 300 million m/s in free-space is 'only' 200 million m/s in glass. But in a world that prizes getting the latest information fast, this fundamental additional latency can sometimes be limiting for many applications. This was dramatized best in the Selma Hayek movie the "Humming-Bird Project", where she builds a set of line-of-sight microwave links to eliminate milliseconds worth of latency between the Chicago and New York bourses.

In this paper Comcast introduces Hollow Core Fibers and the cutting-edge work being done to reduce this fundamental latency and enhance capacity all at the same time. New fiber technology creates a fiber guiding mechanism that has a core that is hollow and consequently allows light to travel in the hollow of the fiber as-if in free space, but along the fiber path!

We describe a system which is a hybrid of hollow core fibers and standard single-mode fibers. Keeping in view that Comcast operates core and access networks this system has amplified and unamplified bidirectional Coherent systems of 400G and 100G wavelengths along with direct detect systems of 40G, 25G and 10G wavelengths all simultaneously on a single strand of fiber, in what we believe to be the first such system in the world.

In addition to describing our test system and initial results, we also analyze some of the benefits in addition to latency reduction that are related to reduced optical non-linearities and other effects and the wider spectrum and the consequent Capacity enhancements possible. Practical deployment strategy of fibers is essential at Comcast, the ability to use a portfolio of fibers for some of the emerging low latency market while also driving fiber technology deeper into the network is of the essence of our approach towards the industry initiative of 10G.

2. Background

Everyone likes to peer into the future, that most inscrutable of entities right in front of all of us. In real life, all of us generally uncover it along with everyone else, but efforts to glimpse it just before everyone else is a passion that drives great technology.

The fastest way for information to travel is at the speed of light in vacuum, that speed, set at 299,792,458 m/s is a universal constant. In other transparent media, the speed of light is slower due to light matter interaction defined as the refractive index of light. Refractive index of light is the ratio of the speed of light in the medium vs. the speed of light in vacuum. For water this number is 1.3, and the mismatch in the speed of light in air and water is what makes a straw in water look like it is shifted. Furthermore, the same effect also allows for reflections at the boundaries and these features are exploited to build optical waveguides to help guide light along non-rectilinear paths.

Optical fiber waveguides were conceived around 1965, and single mode optical fibers, a type of optical waveguide have become the premier means of data transmission for the past 5 decades or more. A careful tradeoff on the geometry, the refractive index differential between the core and the cladding gives rise to our modern Solid Core Single Mode Optical Fiber (SCF-SMF). Standard Single Mode Fiber typically consists of a slightly higher refractive index glass core no more than 9um in diameter surrounded by a slightly lower refractive index glass of 125um cladding. Many different types of optical fibers all more or less following the method outlined above, such as non-zero dispersion shifted fiber and large effective area fibers have been constructed and some of them are in use today as well. In the past 5 decades, every single aspect of the optical fiber has been studied and analyzed, every material composition and build has been researched to create a fiber that has the lowest transmission loss, the highest micro and macro-bend performance and the greatest tensile strength for deployment across the world.

Around 1995, there emerged a revolutionary new concept of optical waveguides, in what looked like a solution looking for a problem. What if instead of solid waveguides guiding light, the light were guided within holes of an optical fiber! Among other things this was a radical concept because it was assumed then that light guiding could only occur when the core had a higher refractive index than the cladding, in this case the situation seemed to be the reverse.

These early fibers were called ‘Holey Fibers’ for the holes in the fibers. Soon reduced latency, higher power delivery possibilities came to be identified with these fibers. But before that, significant issues associated with fiber attenuation, micro and macro bend losses, and production techniques would need to be solved, and are discussed next.

3. Holey Fibers to Hollow Core Fibers

Fiber attenuation is always of prime concern for any optical fiber. Optical fibers have minor imperfections in the core composition, and these lend themselves to light scattering and reflections of very small magnitudes called Rayleigh Scattering in optical fibers. Over long links of fiber, these scattering effects diminish the amount of light that can get thru to the other end and are a primary cause of fiber loss [1,2].

When holey fibers came about initially, they were very hard to build, but in addition the built fibers had very high losses. Some of these fibers were 10 or 20dB/km of loss, while the standard SCF-SMF was then at around 0.25dB/km or less.

There was a new evolution in holey fibers that enabled this loss to become dramatically less, and it was based on creating a lattice like structure in optical fibers. These fibers are called photonic bandgap fibers (PBG) shown on the right in Figure 1. A large central hollow core followed by a lattice structure around would effectively confine light in the hollow of the core and enable light guiding in the transverse direction (i.e., along the fiber length). Such fibers when originally manufactured had lower loss than holey fibers. Furthermore, the micro and macro bending losses of these fibers were quite good. In principle, since the core confinement of light was good or in other words Confinement Loss (CL) is minimal, it was theorized that the fiber loss could be arbitrarily low. However, it was found experimentally that the surface scattering loss due to imperfections in the surface of the lattice structure was so great that the Surface Scattering Loss (SSL) would be a dominant mode of loss of the optical fiber limiting its minimal loss to around 0.65dB/km. This loss value although not very good by SCF standards is still very good for low latency applications and is in use today for various such applications which will be discussed later in the paper.

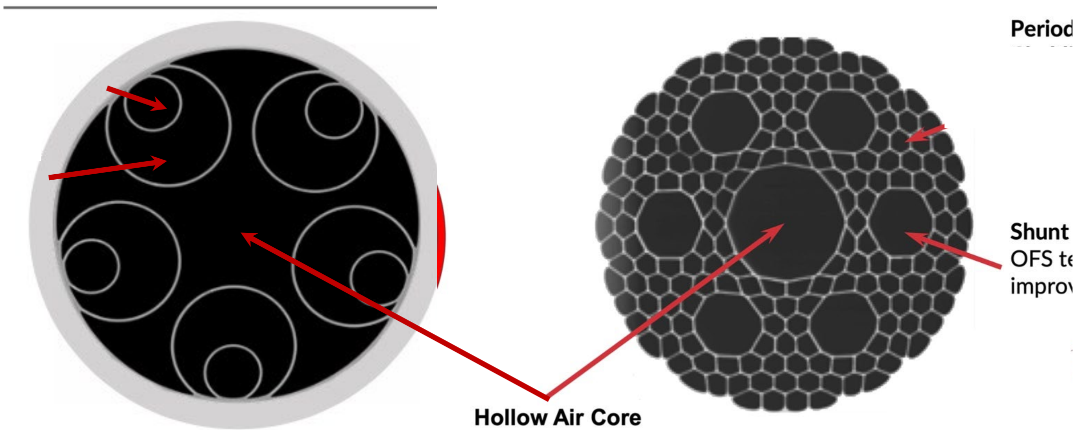


Figure 1 – Illustrating different approaches to Hollow Core Fibers [3,4]

Around the mid 2010s a new type of hollow core fiber has emerged that has the potential to offer lower loss. This is the Nested Anti Resonant Nodeless Fiber (NANF) shown on the left in Figure 1. In analyzing the SSL of the PBG fiber it was found that most of the entire lattice structure did not really do much to guide light, but actively participated in increasing SSL. And furthermore, it was found that having fewer non touching capillary structures guided light just as efficiently without spilling light. It is helpful to think of the light confinement as a series of Fabry Perot structures reflecting light and holding it in the hollow core of the fiber. A further innovation of using nested capillary tubes in the fiber improved core confinement and reduced Confinement Loss. By playing with the capillary thickness and placement further improvement occurred continuous single mode low loss operation across the O and the C bands.

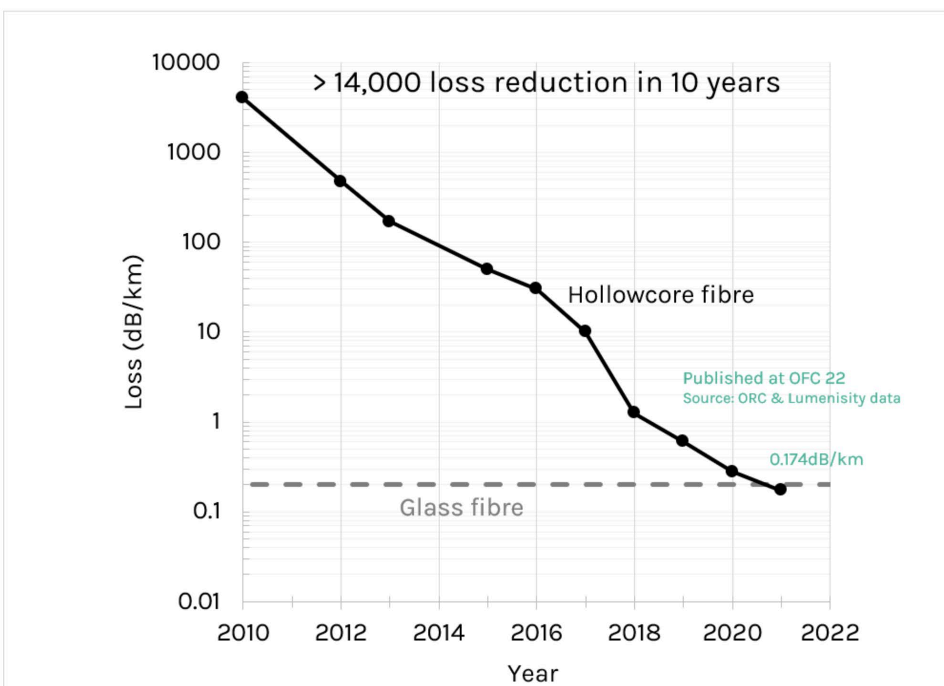


Figure 2 – Hollow Core Fiber Loss over the decades [3]

Figure 2 is a graph of the impressive improvement in anti-resonant fibers in the past decade and a half. True to form, at the post deadline paper at the OFC this year, there were reports of a double nested anti resonant nodeless fiber (DNANF) of 0.17dB/km thus matching the loss of SCF-SMF fiber at the C-Band and at 0.22dB/km at the O-Band thus breaching the loss of the SCF-SMF [5].

As discussed before, the total loss of optical fibers are due to intrinsic mechanisms comprising the material purity and Rayleigh scattering loss, confinement loss and surface scattering loss and extrinsic losses due to micro and macro-bending loss due to cabling or installation. In the HCF, Rayleigh and surface scattering losses are very low, and confinement loss can be decreased by double nesting as well as by increasing the core diameter. But increasing the core diameter would probably increases the bend losses while multiple nestings could increase manufacturing complexity. But in any case, the idea is to let the industry know that such fibers are on the horizon.

4. Latency, Capacity and Reach

Our work on Hollow Core Fibers has primarily focussed on the NANF type of fibers. These fibers offer the potential for low optical loss, have low Chromatic Dispersion, have high power handling capability, a wide bandwidth covering the C+L band, all while having latency that approches the fundamental limit of speed of light in vacuum. Of these, latency reduction is of fundamental importance, while other limitations such as higher losses or bandwidth could be overcome by optical amplification or higher allocated fiber counts.

4.1. The Latency-Capacity Continuum

Today it is common to see 100Gbps, 400Gbps and even 800Gbps type of transport rates per wavelength on core and access networks. But the rise in 5G and other such technologies has also focused our attention on latency or responsiveness of a network. With the understanding that latency and capacity form two independent metrics that define the quality of our network and there are many applications that require one or both metrics.

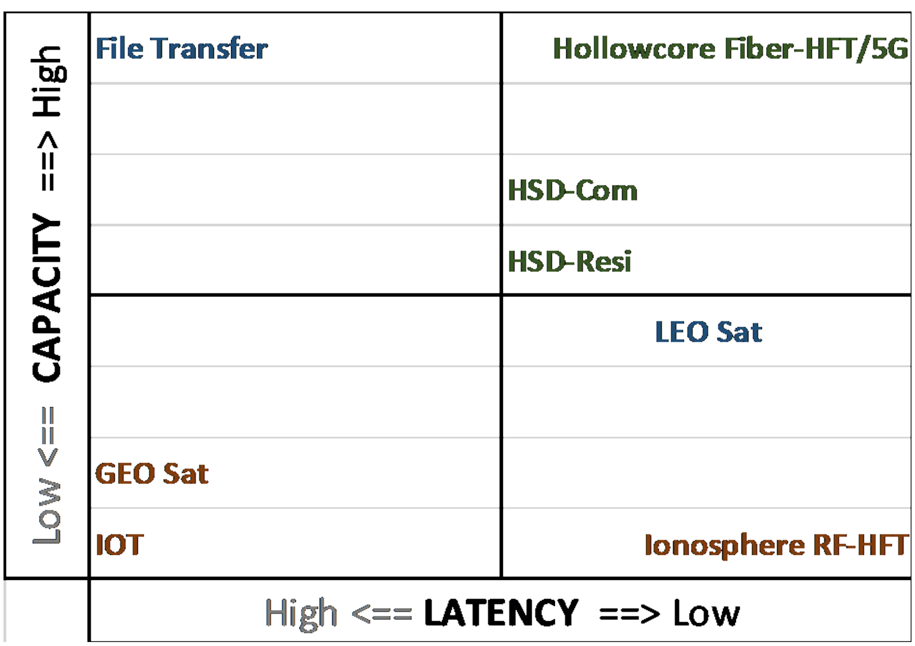


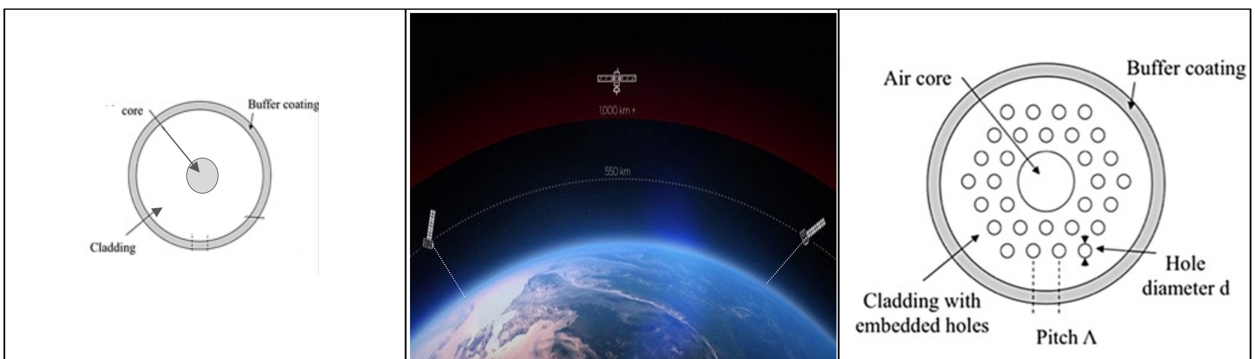
Figure 3 – The Latency - Capacity Continuum

Consider Figure 3, in which Internet of Things (IoT) charecterized by low traffic capacity needs and slow update requirements result in it being in the lower left quadrant. High Frequency traders and 5G with their need for high capacity and very low low latency will fit in the upper right quadrant, these are best served by hollowcore fiber links. Businesses and campuses which do file transfers during the off-peak hours might benefit with very high capacity links but without the responsiveness of low latency needs. RF transmission utilizing the reflective properties of the Ionosphere for low capacity high frequency traders fit in the low capacity and low latency bucket in the bottom right.

Latency is a rather complicated topic depending upon multiple variables. At its most fundamental, it depends upon the time of flight of the physical medium, secondly, it depends upon the variopus electronic switches nd routers that make up the circuit. Finally, it depends upon the various ques and buffers that form at the near and far side that gate information transfer. It is not surprising that industries with tight latency requirements have made great strides in reducing latency of their switches, thus some switches that are used by HFT are directly written in FPGA code and can approach ns latency. The latency of the the physical medium however is of fundamental importance and is described next.

4.2. Comparing SCF, LEO and HCF Latencies

As we have said before, light ravel at roughly 300,000km/s or 300m/us in free space, but travel at 'just' 200,000km/us or 200m/us in SCF-SMF fibers. And the low Earth orbit call Leo is approximately 550 km above the surface of the earth. Therefore with this understanding we can now understand the latency implications of the three scenarios described in Figure 4. The left figure corresponds to time of flight latency of a conventional fiber, the middle corresponds to time of flight latency for a low earth orbit satellites free space links and the one on the right describes latency in a HCF system.



Solid Core Fiber	Low Earth Orbit	Hollow Core Fiber
Speed of light glass = c/1.5 = 200,000 km/s	550km + DISTANCE + 550km speed of light in air/space = c = 300,000 km/s	speed of light in air/space = c =300,000 km/s
Latency = $2*\frac{1.5*D}{c}$	Latency = $2*\frac{1100km+D}{c}$	Latency = $2*\frac{D}{c}$

Figure 4 – Solid Core, Low Earth Orbit and Hollow Core Approaches to Latency

In a regular SCF-SMF, the two-way latency is just twice the distance divided by the refractive index of fiber material, which happens to be around 1.5 (actually ~1.4684 in the 1550nm region).

Many years back, satellite communication was rather latency prone since satellites were located at the geosynchronous/geostationary orbit around 36,000km above the earth accruing a delay of 250ms which rather limited the scope of it in high-capacity communications. Recently, low earth orbit satellites have been launched which are just 550km away, the idea being to cover the earth in a sheath of LEO satellites to offer connectivity around the world. Furthermore, these satellites also can have inter-satellite communications, typically using 100G CFP2 type dual laser bi-directional coherent optics (a more detailed treatment is presented at a different paper in this Conference). Note that inter satellite transmission happens in free space where the refractive index is 1.0. In this case, the latency is significantly reduced, and in the limit may be as small as an additional transit time of 550km to go to one satellite and come back to the earth with the same 550km. Note there that we have not taken into account the processing time in the satellite opto-electronics.

Finally, use of HCF enables one to use the same geographical lines as the SCF-SMF, but with hollow core fiber. Thus, the time of travel is just twice the distance divided by the speed of light.

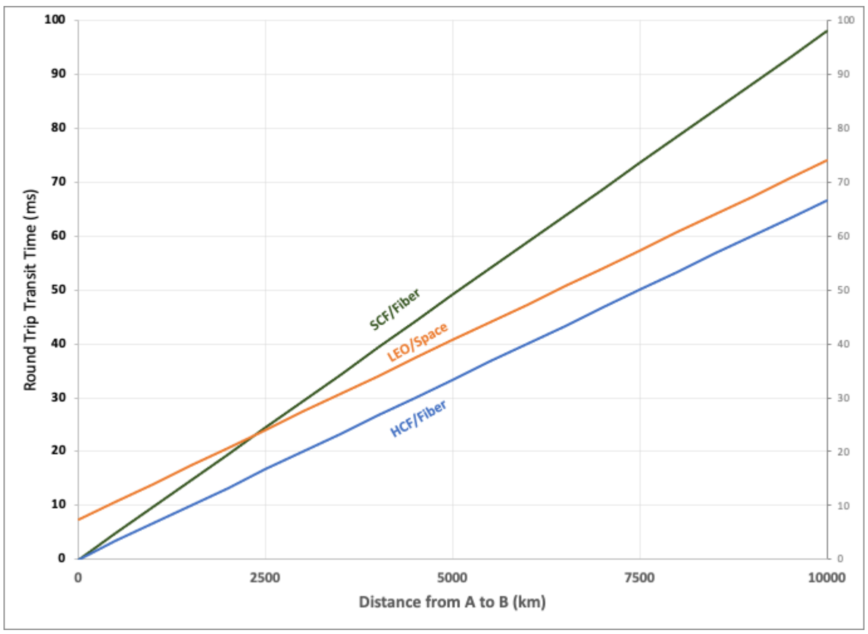


Figure 5 – Comparing Latencies of the Various Approaches

As summarized in Figure 5, HCF is ALWAYS the link with the least latency, but for very short distances, the delta between SCF and HCF time of flight is small, but always 50% faster in HCF than in the SCF. LEO Space communications, on the other hand start out with a higher latency, but by around 2500km, space communications becomes faster than SCF-SMF communications.

The implications of this are vast. If specific companies can figure out LEO sat communications that have very little optoelectronic delays in inter satellite communications, then they would have a huge ability to 'see' the future between the bourses of London and New York for example, which are more than 2500km apart. Within the US, for all locations West of Denver relative to Philadelphia, the LEO communications would have been the same! A hollow core fiber deployment on the other hand along straight line would always have a lower latency and would be at the universal speed limit and would never lead to such arbitrages.

While the case has been made for long haul transport, similar is the case within access networks as well. In the case of 5G front haul, where due to dispersion and latency, around 15km is an accepted distance between towers and central offices, the use of HCF can legitimately increase distances traveled to over 25km for the same latency envelope effectively doubling the area under reach for the cell towers connected to each central office. There is one other aspect of HCF that relating to fiber dispersion which will be described in a later chapter.

4.3. Geographical Flexibility

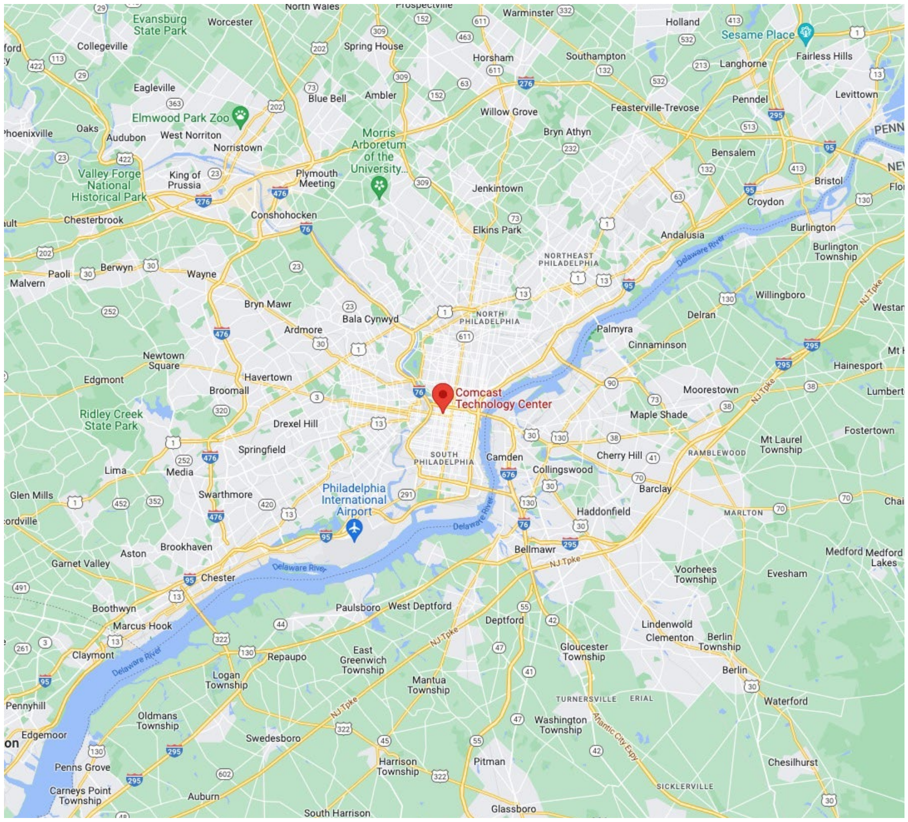


Figure 6 – Increasing the Latency Envelope and Enhancing Geographical Flexibility

There is a geographical flexibility case to be made here for the HCF as well. If we consider that a specific latency is needed from place A to place B, based on standard fiber, but the line between A and B is cut by additional natural or artificial barriers unanticipated at the time of design. In such cases, making a section of the path HCF could give a much-needed latency reprieve and enable the existing design to proceed naturally.

This concept of latency reprieve or latency trade can also be applied to a system in which the number of transactions is also a figure of merit. Here, the lower latency translates in quicker transactions, which in turn could enable - say – high frequency traders on HCF refine their positions continually many more times than the traders on SCF based on the much more rapid conversations.

4.4. Critical Infrastracuture Implications

We previously discussed that the backward compatibility enabled the use of same terminal equipment. While this is true a potential additional benefit in the form of power savings might accrue on account of the fact that individual DSP chips in pluggables may not need to work as hard to compensate for dispersion and optical non-linearities lading to less complex (and lower cost) pluggables and lower critical infrastructure costs.

5. Features of Hollow Core Fibers

The previous chapters have described in detail the evolution of Hollow Core Fibers and the most fundamental advantage of HCF, regarding the ability to offer the lowest latency possible. It turns out that in addition to this fundamental benefit, there are several secondary benefits that make the deployment of HCF (especially NANF) attractive in both core and access networks, what are discussed next.

5.1. Taxonomy of Optical Impairments

Presented below is the well-known 'taxonomy of optical impairments'. Linear impairments such as chromatic dispersion and optical loss along with optical passives are presented in on the right-hand side, while non-linear impairments that depend upon the of light intensity in fiber are arranged to the left. Specifically, we distinguish between non-linear effects due to single wavelength and non-linear effects due to multiple wavelengths one below the other.

Describing effects of nonlinearities and their impact is an interactive process and will only be summarized here in the context of HCF. It must be emphasized that many of the linear and non-linear effects which are much more important for analog transmission of light that is characterized by high power levels and high optical performance requirements have been thankfully reduced in the migration to digital, but yet, many limitations unique to digital transmission still remain and may add up to significant power penalties reducing reach or capacity.

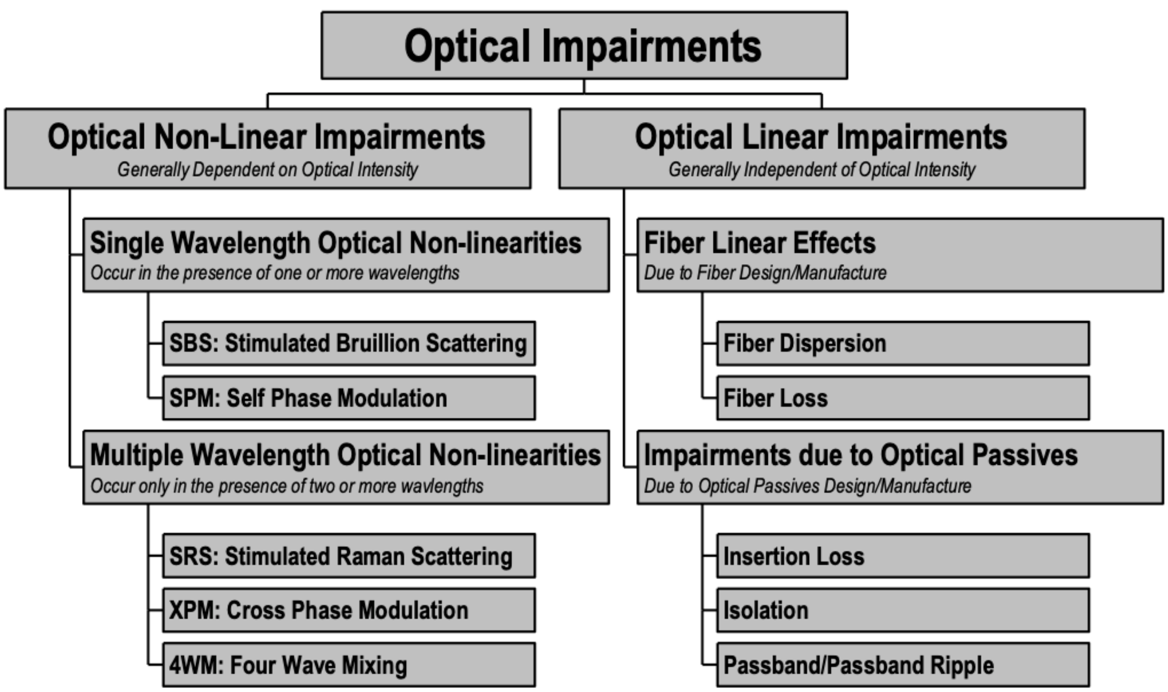


Figure 7 – Taxonomy of Optical Impairments

5.2. Linear Impairments: Fiber loss

Linear impairments are led by fiber loss concerns as fiber loss in present generation of HCF is around 1.5dB/km which limits deployment of long distances without amplification. The generation of dual nested fibers sport a loss of 0.17dB/km, which approaches the loss of SCF-SMF and will be quite suitable for long distance deployments. The current generation of fiber is good however for shorter distances and to proof out a number of other parameters that bear validating. It is important to note that the fiber has a continuous operational single mode region that cover the C and L bands. The bump in loss at the water peaks is attributable to the presence of water vapor (OH ion) in the hollow of the glass, one that may potentially be reduced by an appropriate purge of the core.

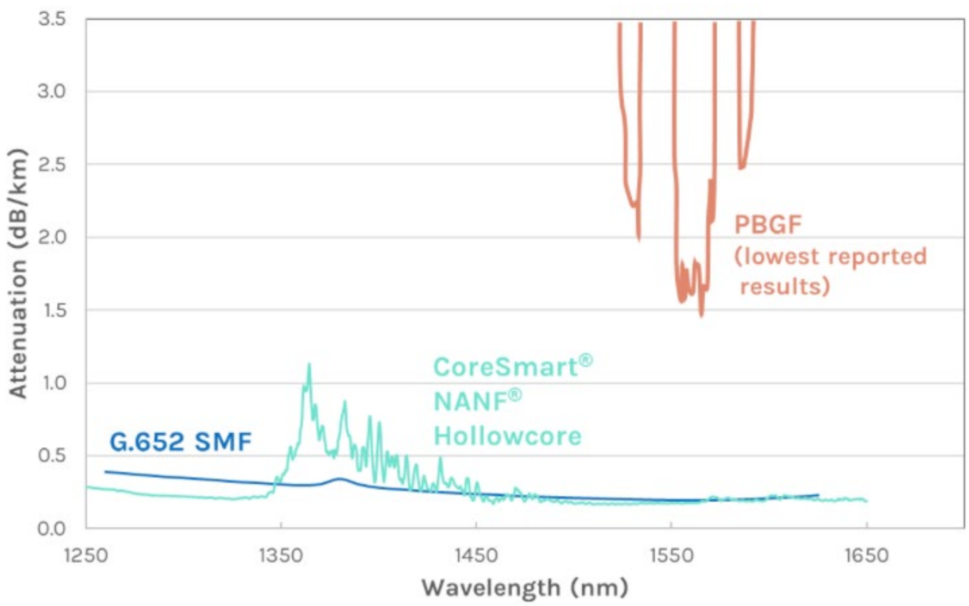


Figure 8 – Illustrating fiber loss vs. wavelength for various fibers [3]

5.3. Linear Impairments: Fiber Dispersion

Hollow core fiber has dispersion that is around 2.5ps/nm.km. For comparison, the SCF-SMF has a dispersion of around 17ps/nm.km in the C-band, yielding a 7x benefit of the dispersion parameter. In real life, this translates to longer reach for baseband transmission where the fiber reach decreases as the square of the ratio between baseband speeds as illustrated in this log-linear graph in Figure 9.

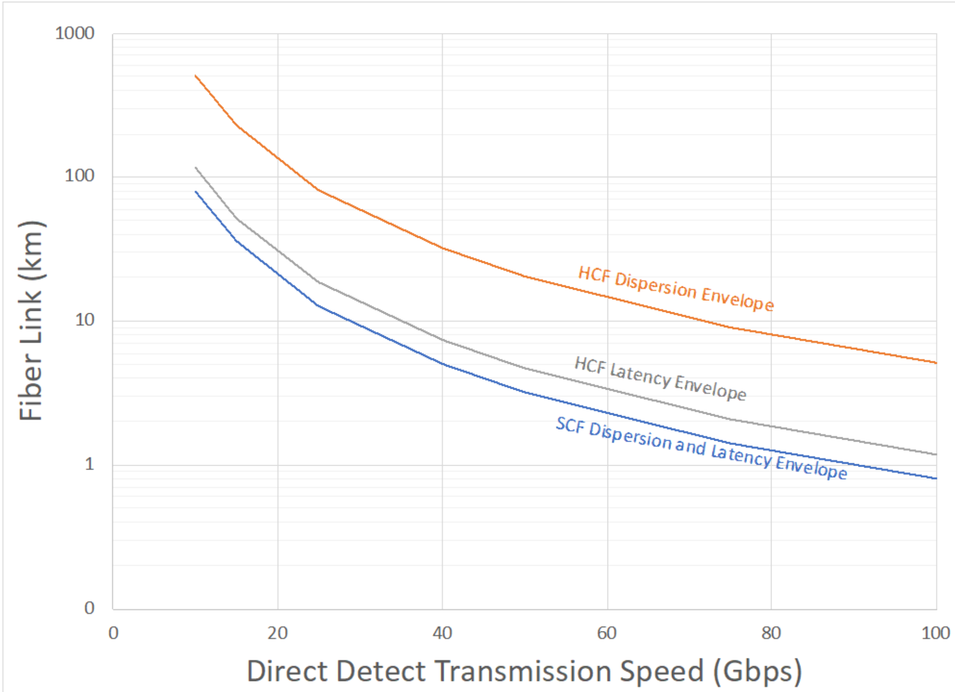


Figure 9 – Illustrating dispersion and Latency envelopes for SCF and HCF

For example, 10Gbps baseband signals routinely transmit over 80km, can now traverse 100s of km with minimal dispersion penalties on the HCF. Similar is the case crucially with 25Gbps which is an eCPRI standard was previously limited to 15km of transmission as that was what was possible over standard fiber, this can now transmit to over 80km as illustrated above. A point to note here is that the latency envelope of eCPRI can now be 25km rather than 15km with the HCF as well, thus indicating that HCF could bridge both the latency and reach envelopes as indicated above for various speeds.

In order to verify the benefits of the HCF fiber in access network applications, we verified error free performance of links using SFP28 DWDM CPRI and 40G QSFP DWDM optics over 20km of HCF currently deployed in the Comcast campus. In this verification optical amplification was required to overcome the HCF insertion loss. For comparison purpose we also ran performance tests with 10 and 20km of SMF and, as expected, we could verify the SMF dispersion limitation leading to system breakdown at 7 and 13km of standard fiber, respectively, without dispersion compensation. These results are presented in a later section, Wideband Direct Detect with HCF.

5.4. Linear Impairments: Fiber Splicing and Backwards Compatibility

It is common to find specialized fiber ribbon splicing equipment and software that can splice 12 or more fiber cores at the same time. Similarly, splicing equipment and software is available to field splice HCF.

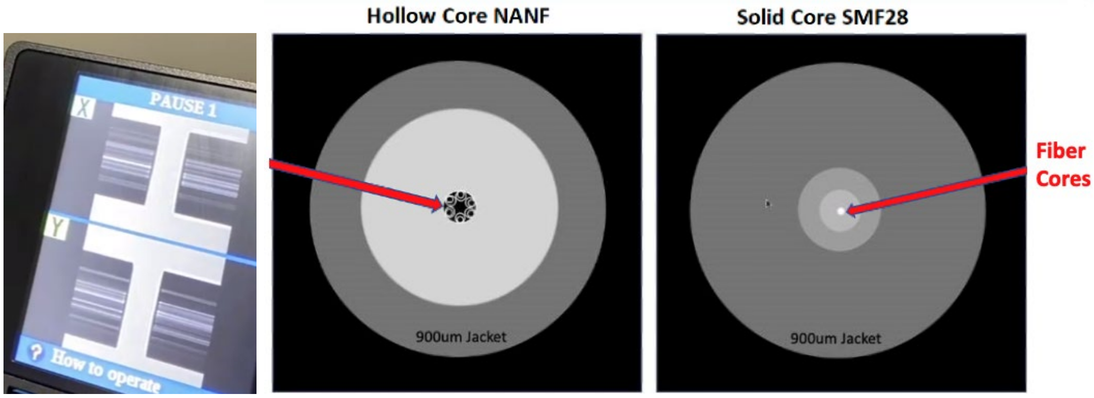


Figure 10 – Splicing HCF-HCF and HCF-SCF fiber cores

But splicing a HCF to SCF is much more complicated as the geometry of the two fibers are different. Therefore, fiber adapter cables that have HCF on one end and SCF connectors at the other end are specially made in the factory and then used to light up fibers with conventional optical equipment in headends, hubs and nodes. This keeps ALL of the terminal equipment completely backwards compatible with all other equipment while enabling the use of HCF in the field.

In other papers in this conference, we have presented on new underground construction method called the CiC in which micro-fibers re-enter the conduit already holding RF cable and reuse the duct/conduit infrastructure already in use with minimum disruption. Most micro-fibers have 6 tubes within with 12 fibers each in each tube. In this case, one or more tubes could be dedicated to hollow core fibers while others for standard fiber and thus a portfolio of fibers may be installed when the conduit is re-entered. This type of innovative deployment may help bring fiber to the neighborhood where high-capacity latency sensitive endpoints may be located. This concept of a portfolio [6] of fibers is more general of course and may be used in other deployments as well in core and access fiber platforms.

5.5. Non-Linear Impairments:

Optical fibers provide excellent light guiding but in doing so also provide a long interaction length for light-matter interaction. When optical intensities increase in an optical fiber, this leads to non-linearites. All Non-linearites increase with fiber intensity. Some such as SBS stimulate the reflection of light back to the source, others depend upon the non-linear index of glass, which increase with optical intensity. Also called the Kerr effect, this has the unfortunate result that the light speed is modified by the light intensity. When this happens, either due to the self-channel intensity or adjacent/cross channel intensity, a range of non-linear effect arise. But the worst non-linear effect by far is the Four Wave Mixing effect. So called because the fiber itself generates ‘beats’ due to multiple wavelengths that can have a catastrophic effect on transmission. To make matters worse, these non-linear effects also interact with linear effects such as dispersion and polarization and can be intermittent. To tamp down on these effects requires a deep understanding of all effects and with it an effective wavelength plan and robust modulation format.

With fixed locations for amplification and the rise of flex grids and the desire to use C and L Bands together, the practical outcome of these non-linearities is unfortunately a rather severe limit on launch power. But low launch powers have the adverse effects of needing multiple amplification spots and the consequent degradation in signal quality. Furthermore, many non-linearites get exacerbated with the optical amplifiers themselves as these are also fiber-based devices. The net result is a delicate balance.

Not so the case in HCF. Since the core is hollow there is the elimination of light matter interaction. Furthermore, the non-linear index of air/vacuum is non-existent, therefore quite a large amount of light can be packed in to the HCF. The ability to launch larger amounts of light could lead to sparser amplifier spacing and in turn lead to longer reaches.

6. Hollow Core Fiber in Comcast

Late last year, Comcast acquired 20km of cabled HCF, of which 10km was cabled for inside plant performance and the other 10km for outside plant performance. These fibers were terminated in SC-APC adapters via the HCF-SCF adapter cables mentioned before. We began by ensuring that the fiber was reciprocal, by which we mean the loss tested identical from either side of the fibers. It turns out that both fibers had approximately 1.5dB/km of loss and the HCF was indeed reciprocal. Having done that, we deployed the fiber in Comcast.

The HCF was then deployed in a system comprising multiple direct detect and coherent systems. The configuration was 10km of the ISP HCF followed by various lengths of SMF and then finished up with the 10km of OSP fiber. All ends of the fibers are all connected with standard SC-APC connectors thus ensuring total backwards compatibility for this hybrid SMF and HCF system.

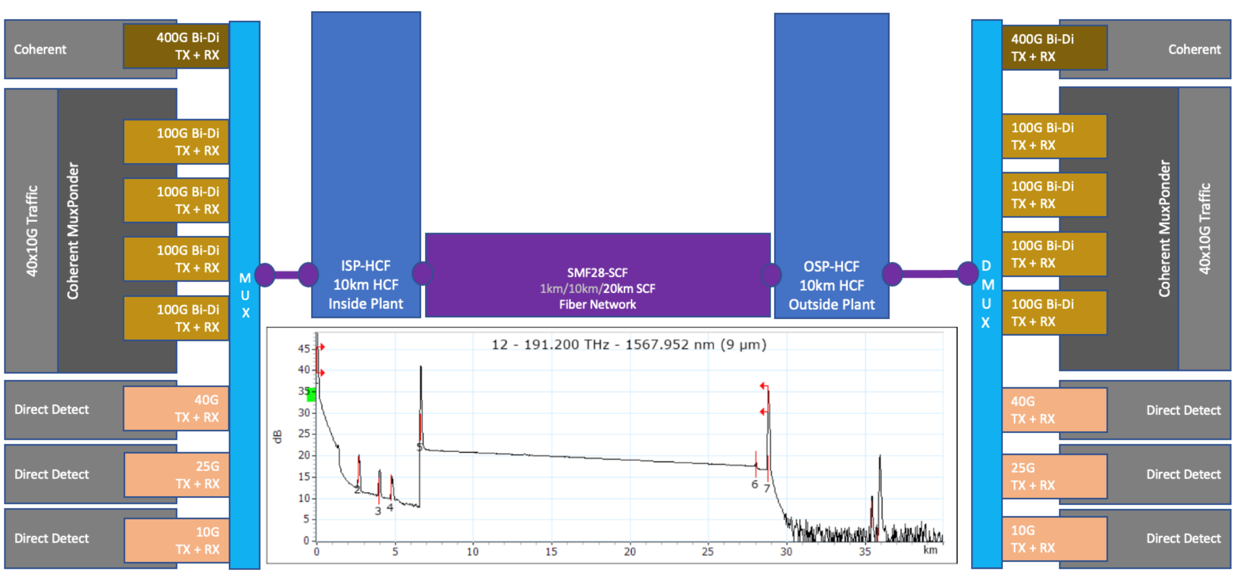


Figure 11 – Block Diagram Illustrating the Comcast Deployment

OTDR scanning of the HCF is a surreal experience as illustrated in Figure 11. Since there is no Rayleigh scattering in HCF, the entire section of fiber of 10km shows as if it is 'cut' on the OTDR trace. The only indication that the fiber if fine is based on the reflective peaks on the trace at the ends of the fiber due to the SCF-HCF adapter cables. The next 20km of fiber is unremarkable given that it is a standard SMF fiber with nominal loss of 0.25dB/km and its associated Rayleigh scattering. The last 10km of HCF fiber is similarly to the first 10km appears 'cut' save for the reflective peak at the end of the total 40km of cable. One other point to remember here is that the HCF although 10km long, appears to be just 6.8km! This is because the refractive index in the OTDR is set to that of 1.4684, if on the other hand it were set to 1.003, which is the refractive index of air, the result would have been that the HCF would show 10km, but the SMF would then have showed 14.7km.

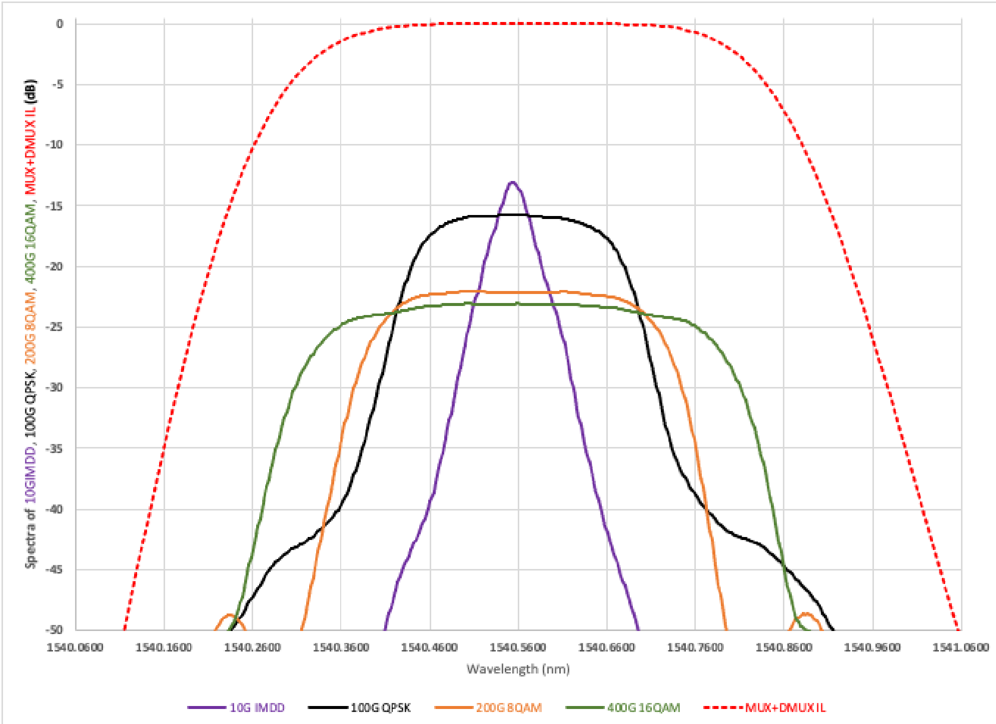


Figure 12 – Illustrating various direct detect and coherent spectra and the passives passband

In a different paper at this conference, we have discussed Comcast plan to converge various wavelengths onto a single optical fiber in the access plant [7]. The picture above shows that the optical filters used in the access plants can handle all wavelengths up to 400Gbps a fact also tested in the system here.

A unique feature of our system is that it is bi-directional, where a single fiber was used to interconnect the two end points. The main reason for the BiDi approach is the need to understand how such systems perform using HCF with the possibility of preserving fiber, HCF or SMF. The system described in the figure below describes the BiDi system where coherent links are combined with direct detect system of 10G, 25G and 40G wavelengths to deliver different types of services simultaneously (DAAS, BERT testing, etc.) in the same string of fiber. We believe that is the first implementation of such system in the world. The optical spectrum analyzer capture depicted in Figure 13 shows the actual spectrum utilization for this trial.

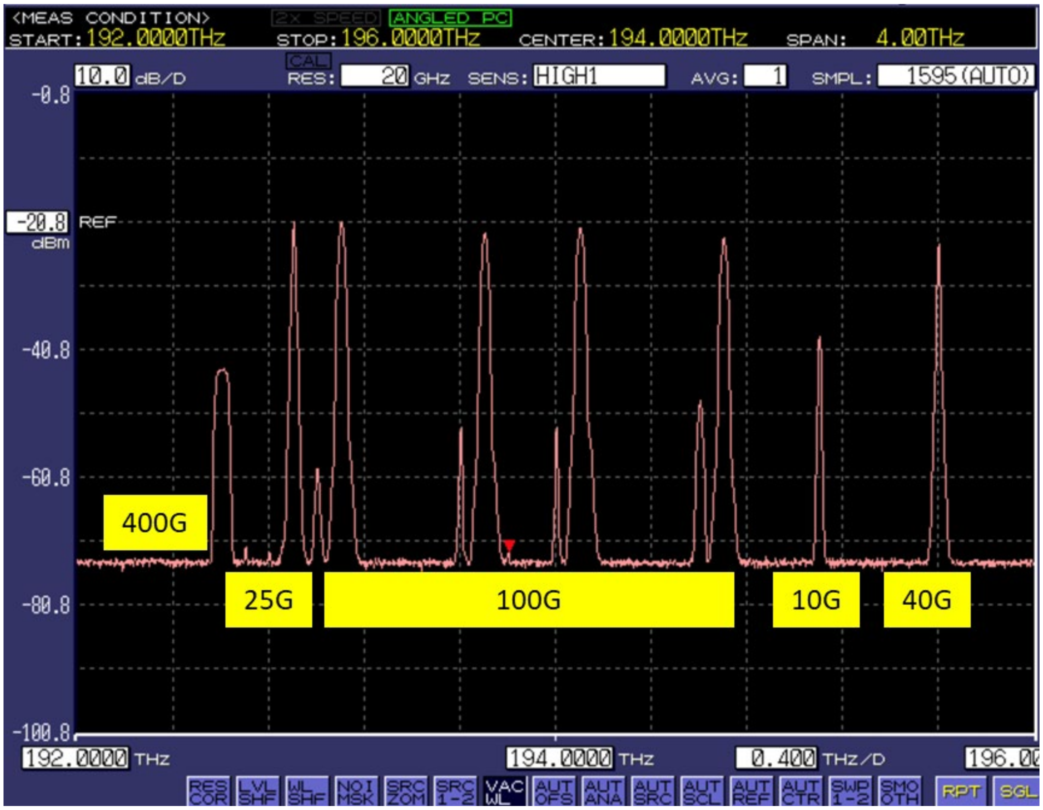


Figure 13 – Bi-Directional Optical Wavelengths over the Comcast HCF Link

Towards that end, as the spectrum graph above shows, we tested bi-directional transmission on a single fiber comprising

- Coherent 400Gbps using 16QAM 63GB system
- Coherent 100Gbps using QPSK 32GB system
- Direct detect 40Gbps NRZ
- Direct detect 25Gbps NRZ to simulate CPRI data
- Direct detect 10Gbps NRZ

And were successful in closing all the links over 20km emphasizing the viability of Comcast vision over multiple fiber types.

6.1. Establishing Latency Improvement using a Hybrid Loop Test

To verify the latency improvements in our system we devised a test set-up using standard 10G test equipment. The approach consists in cascading the 10G traffic from a traffic generator back and forth using back-to-back the 10G optics connected to the CFP2 optics trough an aggregation switch. The diagram below shows how the 10G traffic is propagated back and forth trough the CFP2 to produce the 100G traffic. In our implementation we actually used a loop test with the same 10G traffic to go back and forth over 20km of fiber 40 times with the 80 10G SFP+ devices aggregated to 8 of the 100G CFP2 devices. Overall, in this hybrid fiber/electronic loop test [8], we actually propagated the 10G signal thru

2*20*40 = 1600km. We then repeated this test with standard single mode fiber as well and used the test equipment to track packet errors, latency and jitter.

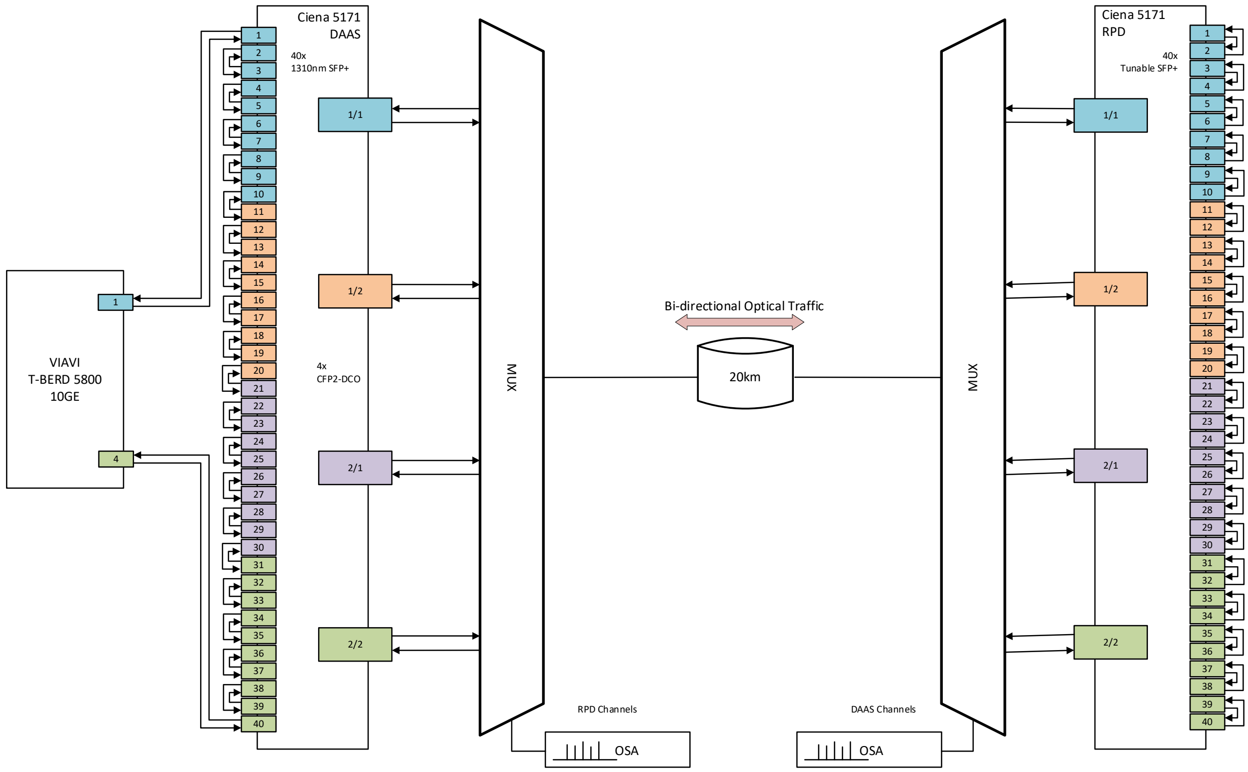


Figure 14 – The Hybrid Loop Test Illustrating Latency Reduction

Presented below is the test data collected and summarized. In it is seen that the latency on HCF is much lower than that on standard fiber. The 8972us delay on HCF compares to 11,330us delay in the SCF-SMF case. We also measured the latency of a link combining 20km of HFC and 10km of SCF-SMF, which led to 17,352us delay.

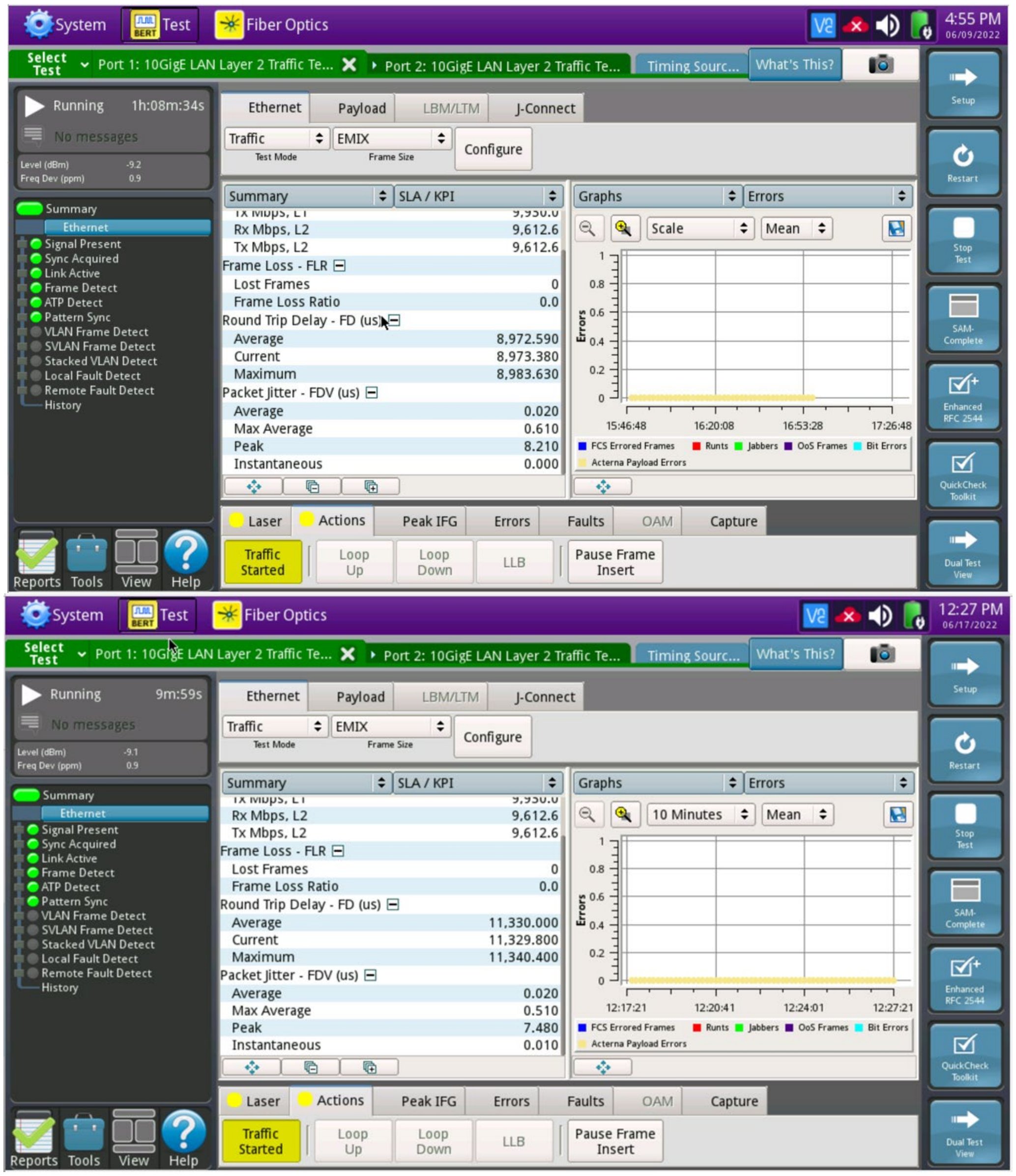


Figure 15 – Illustrating Latency improvement with HCF (top) over SCF-SMF (bottom)

6.2. Spider Diagram Grand Summary

Below in Figure 16, we present a Spider Diagram showing the key comparison points to summarize the main differences between the HCF and the SMF. The assumption here is to use the relative performance between the two fiber types.The key parameters used for the diagram vertices are purpose were latency, insertion loss, cross-talk (linear and non-linear), cost, and power consumption (green factor).

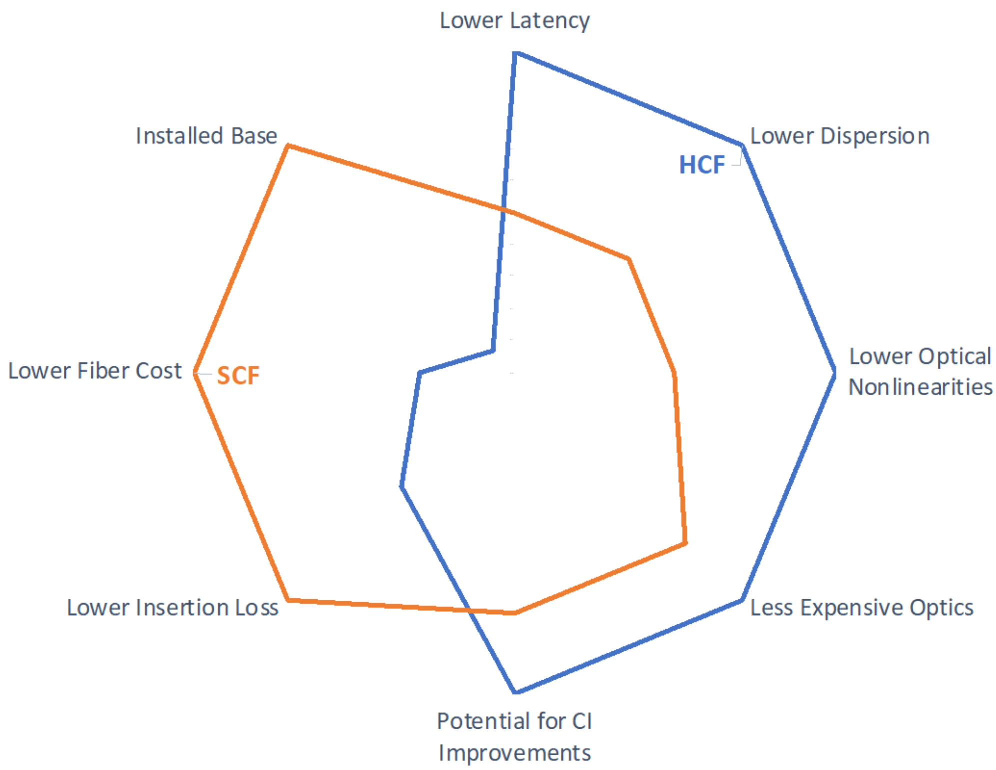


Figure 16 – Qualitative Comparison of Fiber Attributes

In addition to describing our test system and initial results, we also analyze some of the benefits in addition to latency reduction that are related to reduced optical non-linearities and other effects and the wider spectrum and the consequent Capacity enhancements possible. Practical deployment strategy of fibers is essential at Comcast, the ability to use a portfolio of fibers for some of the emerging low latency market while also driving fiber technology deeper into the network is of the essence of our approach towards the industry initiative of 10G.

7. Conclusion

In this paper we discuss the role of HCF in delivering different types of services over the access networks. We reviewed the history of HCF fibers and discussed some of the main attributes including a combination of minimum latency and non-linear impairments that help drive capacity and reach with continual improvements in HCF technology. We pointed out features that make HCF attractive not only in long haul networks, but also in access networks. While HCF can be a key tool for Comcast to provide low latency services in a cost-effective way. Its combination with traditional SMF provides the great flexibility to our designers to accomplish these goals.

Of particular note in this paper is our report for the first time in our knowledge of successful bi-directional transmission of optical signals across a hybrid HCF/SCF plant with a converging of multiple direct detect and coherent signals ranging from 10Gbps to 400Gbps on a single HCF fiber plant.

Abbreviations

AP	Access Point
Bps	Bits per second
BERT	Bit Error Rate Test
BiDi	Bi-Directional
C Band	Conventional Band (1530 to 1565 nm)
CL	Confinement Loss
CFP2	C Form-factor Pluggable 2 (100Gbps)
DAAS	Distributed Access Architecture Switch
DCM	Dispersion Compensation Module
DNANF	Doubled Nested Anti Resonant Nodeless Fiber
DSP	Digital Signal Processing
eCPRI	Enhanced Common Public Radio Interface
EDFA	Erbium-Dope Fiber Amplifier
FPGA	Field-Programmable Gate Array
HCF	Hollow core fiber
HFT	High Frequency Trading
Hz	Hertz
IoT	Internet of Things
ISP	Inside Plant
K	Kelvin
LEO	Low Earth Orbit
NANF	Nested Anti Resonant Nodeless Fiber
NRZ	Non-Return-to-Zero
O Band	Original Band (1260 to1360 nm)
OFC	Optical Fiber Conference
OSP	Outside Plant
OTDR	Optical Time Domain Reflectometry
PBG	Photonic Band Gap
QAM	Quadrature Amplitude Modulation
QSFP	Quad Small Form-factor Pluggable transceiver (40, 100Gbps)
QPSK	Quadrature Phase Shift Keying
SC-APC	Standard Connector - Angled Physical Contact
SCTE	Society of Cable Telecommunications Engineers
SCF	Solid Core Fiber
SMF	Single Mode Fiber
SFP28	Small Form-Factor Pluggable 28 (25/28 Gbps)
SSL	Surface Scattering Loss

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