Trends in optical access and in-building networks

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Trends in optical access and in-building networks

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Abstract
As users require ever more speed, variety and personalization in ICT services, the capacity and versatility of access networks needs to be expanded. The first generation of point-to-point and of point-to-multipoint time-multiplexed passive optical networks (PON) is being installed. More powerful wavelength-multiplexed and flexible hybrid wavelength-time multiplexed solutions are coming up. Radio-over-fibre techniques create pico-cells for high-bandwidth wireless services. Next to bringing the bandwidth luxury to the doorstep, it must be distributed inside the user’s home. By advanced signal processing techniques, high-capacity wired and wireless services are jointly distributed in a low-cost converged in-building network using multimode (plastic) optical fibre.

T. Koonen

Ton (A.M.J.) Koonen was with Bell Laboratories of Lucent Technologies for more than 20 years, as technical manager of applied research in broadband systems up to end 2000. From 1991 to 2000, he also was a part-time professor at Twente University. Since 2001, he is full professor in the COBRA Institute at Eindhoven University of Technology, and chair of the Electro-Optical Communication Systems group since 2004. He is a Bell Labs Fellow since 1998, IEEE Fellow since 2007, and elected member of the LEOS Board of Governors since 2007.

Ton’s research interests include broadband fibre access and in-building networks, radio-over-fibre networks, and optical packet-routing networks. He has led and contributed to many European and Dutch projects in these areas.
Extended Abstract

As the thirst of users keeps increasing for higher capacity, more diversity and more personalization of services, the capacity and versatility of access networks needs to be expanded. Next to fast internet and high-definition video services, peer-to-peer file exchange and multi-party video-rich gaming are driving the need for bandwidth. Optical fibre is coming in, in order to relieve the shortcomings of the copper network, and also is able to outperform the power consumption of today's electronic solutions. Moreover, by exploiting the wavelength domain optical fibre is uniquely capable of integrating services with widely differing characteristics independent from each other into a single infrastructure.

First-generation fibre-to-the-home (FTTH) networks are being installed in point-to-point (P2P) and point-to-multipoint (P2MP) time-multiplexed passive optical network (PON) architectures. As a major part of the infrastructure is shared among the users, the PON architecture may offer lower installation and maintenance costs beyond a certain reach and number of users, but it requires a well-tailored medium access control protocol for fair sharing of the capacity among them. Most popular nowadays is the time-division multiple access (TDMA) protocol, where functions can be readily implemented with digital electronics. It is being used in BPON (ATM-based, up to 622 Mbit/s symmetrically), GPON (Gigabit PON, with speeds up to 2.5 Gbit/s, for ATM and also Ethernet packets plus native TDM), and EPON (Ethernet PON, optimized for variable-length Ethernet packets). Alternatively, one may consider Subcarrier Multiple Access (SCMA), requiring more costly RF electronics, or Optical Code Division Multiple Access (OCDMA), requiring more costly optical spectrum slicing filters. Gaining popularity is Wavelength Division Multiple Access (WDMA), where each user on the WDM-PON gets an individual pair of wavelengths for up- and downstream communication, thus in effect getting a P2P link (with its advantage of easy per-user upgrading) on a P2MP physical infrastructure. With so-called 'colour-less' optical network units (ONUs) at the user side, using for instance reflective semiconductor optical amplifiers, more expensive wavelength-specific ONU solutions are avoided; this reduces the costs of the WDM-PON. Hybrid WDM-TDM PON networks can combine the large multiple-channel capacity offered by WDMA with the dynamic bandwidth sharing enabled by TDMA. Notably for PONs with larger ONU numbers and longer reach such hybrid schemes are attractive. Augmented with dynamic optical routing, capacity-on-demand with remarkably reduced congestion probability can be provided, while also improving the efficiency by which the resources installed in the local exchange are used.

For supporting broadband wireless services in fixed wireless access, radio over fibre (RoF) techniques enable to consolidate the microwave signal generation and modulation functions in a single site, which facilitates upgrading and more comprehensive radio schemes. Advanced optical techniques generate extremely pure microwave carriers, and thus enable comprehensive radio signal constellations for high-capacity wireless data links. Dispersion-tolerant RoF techniques support long-reach operation, and link switching in reconfigurable architectures.

Next to bringing the luxury of a high bandwidth to the doorstep by means of FTTH, it must be distributed inside the user's home. As cost is an even more important factor there, easy-to-install large-core multimode (plastic) optical fibre is an attractive medium for implementing a converged single infrastructure which can support wired as well as wireless broadband services. Comprehensive signal modulation formats, such as multi-tone quadrature amplitude modulation schemes, enable to transport high-capacity data wired services via the highly-dispersive fibre infrastructure. Dispersion-robust RoF techniques can support pico-cell radio cell architectures. Using optical routing techniques, such cells may be dynamically merged into reconfigurable wireless private networks, in response to changing traffic patterns.
Trends in Optical Access and In-Building Networks

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Outline

- BB access trends
- PON multiple access techniques (TDMA, SCMA, OCDMA, WDMA)
- TDM-PON solutions (BPON, EPON, GPON)
- WDM-PON
- WDM-TDM reconfigurable optical access
- Radio over fibre
- BB in-home optical network techniques
- Concluding remarks
**Telecommunication networks**

- **Global Network**
  - ultra-long reach
  - ultra-high capacity

- **Metropolitan/Regional Area Optical Network**
  - ultra-fast packet routing

- **Client/Access Networks**
  - variety of media
  - high traffic dynamics
  - cost-conscious
  - user mobility

**Homo Zappiens**

- **Homo Zappiens**
  - high speed
  - multi-tasking
  - iconic skills
  - connected
  - learning by playing
  - instant payoff
  - fantasy
  - technology as friend

- **Homo Sapiens**
  - conventional speed
  - mono-tasking
  - reading skills
  - stand alone
  - separating learning and playing
  - patience
  - reality
  - technology as foe

→ fast growing need for broadband capacity at home and in access; broadband internet traffic, packet-based

[Wim Veen - TU Delft]
**BB penetration ratios**

OECD Broadband subscribers per 100 inhabitants, by technology, Dec. 2007

- **Japan**: 10.52 M FTTH (13.48 M DSL) connections in Dec. 2007

**FTTH as fraction of broadband connections**

Percentage of fibre connections in total broadband subscriptions, Dec. 2007

Source: OECD
**FTTH topologies**

- **P2P**
  - individual upgrading
  - cheap Ethernet P2P transceivers
  - fibre-rich

- **P2MP – active star**
  - fibre-sharing
  - remote powering
  - FTTC, FWA

- **P2MP – passive star**
  - fibre-sharing
  - minimum maintenance
  - easy overlay for broadcast services
  - lower CAPEX* than P2P (for longer feeders and/or more users)

"PON – Passive Optical Network"

**Costs P2P vs P2MP (CAPEX view)**

- number of ONUs $N_1 < N_2$
- fixed costs $C$: OLT, ONUs, splitter
- cost break-even at cable length $L_0$; $L_0$ dep. on $N$
- for $L < L_0$, P2P cheaper than P2MP
- for high $N$, P2MP may always be cheaper

**OPEX** view:
repair of feeder cable break easier in P2MP than in P2P

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- PON multiple access techniques (TDMA, SCMA, OCDMA, WDMA)
- TDM-PON solutions (BPON, EPON, GPON)
- WDM-PON
- Dynamically reconfigurable optical access
- Radio over fibre
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Multiple Access – Time Division

TDMA upstream:

- time-interleaving upstream packets (using request/grant protocol, ONU sends packet in timeslot granted by headend station; may send multiple packets when multiple grants)
- statistical multiplexing gain
- requires time synchronisation → dependency between data channels from ONUs
- burst-mode receiver in headend station
- used in BPON, EPON, and GPON

**Multiple Access - SubCarrier**

**SCMA upstream:**

- fully independent data channels
- no time synchronisation required, no multiplexing gain
- requires RF analog OE functions at OLT and ONUs → expensive
- nodes may send at nominally same wavelength
  → issue: optical beat noise interference with data spectra at OLT Rx

Subcarrier multiplexing downstream

- multiple services on separate electrical carriers
  a.o. for CATV broadcasting (as overlay in PON, or in Hybrid Fibre Coax networks)
- issues:
  - laser clipping, due to over-modulation
  - clipping noise
  - intermodulation products, due to non-linearities
**Multiple Access – Optical Code Division**

OCDMA upstream:

- time-sliced code, or wavelength-sliced
- fully independent data channels, asynchronous, no multiplexing gain
- limited no. of codes → limited no. of users → 2-dim. λ-t code
- issue: with t-code, high line rate (bit rate * # chips/bit)
- issue: with λ-code, larger spectral width → larger fibre dispersion
- issue: x-talk due to imperfect code orthogonality

**Multiple Access – Wavelength Division**

WDMA upstream:

- fully independent data channels: functionally equivalent to P2P
- power budget improved w.r.t. λ-independent power split
- no multiplexing gain
- specific wavelength per node → need for ‘colourless’ ONU
- issue: broadcast overlay, requires bypassing WDM mux
- hybrid WDM-TDM PON: enables more users on the PON, + multiplexing gain
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APON/BPON (ITU-T G.983.1, 1998)

General characteristics

- 155/622 Mbit/s
- CC
- LT
- AN
- NB
- BB
- ONU
- 1:32 (64)
- 10-20 km

- by FSAN (established in 1996)
- ATM cells (53 bytes, + 3 bytes BPON overhead for a.o. grants and BM)
- $\lambda_{\text{down}} = 1480 .. 1580$ nm
- $\lambda_{\text{up}} = 1260 .. 1360$ nm (cheap FP lasers at ONUs)
- differential fibre distance: 0-20 km
- optical path loss: class A 5-20 dB, class B 10-25 dB, class C 15-30 dB

**Timing ranging**

- **measure distance** (OLT sends ranging grant, upon receipt an ONU responds by sending ranging cell, OLT calculates distance from roundtrip delay)
- **insert equalisation delay**

→ puts ONUs virtually at equal distance from OLT, which facilitates synchronisation

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**Amplitude ranging**

- burst-mode receiver at OLT, fast decision level setting
- adapt also transmit power of ONU *

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*Power Leveling Mechanism*: in GPON G.984.2 in 3 steps of -3 dB

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[P. Vetter, 2001] amjk 17

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[P. Vetter, 2001] amjk 18
**Broadband overlay (ITU-T G.983.3, 2001)**

- restrict APON downstream spectral window
- for additional digital services, or video distribution
- high WDM isolation required if electrical spectra of APON and overlay services overlap

**BPON protection (ITU-T G.983.5, 2002)**

**Type B: feeder fibre protection**
- TC protocol executes re-ranging after failure detection and optical switching
- opto-mechanical switch (expensive)
- limited protection

**Type C: full system duplication**
- all equipment normally working → fast restoration
- also branch lines and ONUs protected
- may include unprotected ONUs

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[F. Effenberger et al., IEEE Comm. Mag., Dec. 2001]

[ITU-T Rec. G.983.5]
**Ethernet PON (EPON)**

- standards set in IEEE 802.3ah Ethernet First Mile Task Force, in 2001
- Point-to-Multipoint (P2MP) optical Ethernet
- full duplex, no CSMA/CD
- physical layer largely similar to BPON
- variable packet length, up to 1518 bytes
- Gigabit Ethernet rate (1.25 Gbit/s) and frame format, incl. 25% line coding overhead (8B10B)
- Ethernet offers
  - high bandwidth,
  - low cost,
  - IP efficiency,
  - full services,
  - simplicity
- but (in contrast to ATM)
  - no built-in QoS → QoS has to be handled at IP level
  - issues with real-time services such as voice (due to latency and jitter)

**GPON (ITU-T G.984.1, 2003)**

- by FSAN
- max. logical range 60 km
- max. physical reach 10 to 20 km
- max. differential range 20 km
- down λ=1480 .. 1500nm, up λ=1260 .. 1360nm
- max. split 128
- max. mean signal transfer delay 1.5 ms
- commercial solutions available

- FEC in downstream & upstream (RS(255,239) block code, high code rate of 93.7%, can correct bursts of 50 bits)

- Supports
  - native ATM (like G.983)
  - native packet (i.e. not over AAL5/ATM), and native TDM, by GPON Encapsulation Method

GPON TC efficiency

- high efficiency: 95% of bandwidth can be used for IP data transport in E-GPON (Ethernet mode GPON)
- comparison with Gigabit Ethernet:

Assumption:
- 32 ONUs, every ONU is served every 0.75 ms
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Fixed wavelength-routed PON

- Passive Photonic Loop [Bellcore, 1989]
- needed in ONU for upstream:
  - λ-specific laser (→ expensive stock maintenance),
    or colourless solutions:
    - reflective modulator (→ source-free ONU; requires reflections-lean link),
    - spectrally sliced broadband source (e.g., LED, or ASE from EDFA; → limited power budget), or
    - injection-locked FP-LD or RSOA

AWG = Arrayed Waveguide Grating
Sliced SLED + Reflective SOA

- For downstream: one DWDM laser per user in L-band
- For upstream: SLED with –10 dBm/0.1 nm in C-band
- 40 users, each 0.4 nm bandwidth, 1.25 Gbit/s per user upstream, over 20 km SMF
- AWG in AN with 100 GHz channel spacing
- APD receiver
- Issue: reflections in fibre link

[Ref: F. Payoux et al., ECOC05]

Link loss budget using CW-fed RSOA

- $P_{r}(t) = \left( A_1 + A_2 \cdot G \cdot \epsilon \cdot x(t) \right) P_{c, CW}$
- Extinction ratio of received signal
  - $\epsilon' = \frac{P_{r, x}}{P_{r, g}} = \frac{1 + A_2 \cdot G \cdot \epsilon}{1 + A_2 \cdot G}$
- Power penalty
  - $\Delta P_r = 10 \log \left( \frac{1 + \epsilon'}{1 - \epsilon'} \right)$ [dB]

$\rightarrow$ link loss budget decreases when link reflections increase

[Ref: F. Payoux et al., ECOC05]
Self-injected RSOA

- RSOA lasing, locked to Bragg wavelength of FBG (over 24 nm in C-band), SMSR>25dB
- 1x16 AWG-s, 200GHz channel spacing
- FBG on same silica material as the AWG → no temperature-induced λ mismatch
- 1.25 Gbit/s transmission
- APD receivers at OLT
- issue: spurious reflections in AN-ONU link

[S.-Y. Jung et al., OECC08, WeA.4] amjk 29

Integrated reflective transceiver

- colourless ONU, using a reflective SOA
- optical functions in quantum-dot InP IC, electronics in silicon 10 Gbit/s
- with bulk devices, >1.25 Gbit/s achieved

SOA modulator:
- Modulating rate up to 1Gbit/s
- Fibre-fibre gain up to 9 dB at 90 mA injection current

Photodetector:
- Responsivity up to 0.4 A/W at -2V
- Bandwidth up to 25 GHz

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Multiple access on the PON

TDM-PON
- flexible sharing of LT capacity
- limited number of time slots per user
- congestion at high loads

WDM-PON
- each user own \(\lambda\)-channel
- no congestion
- virtual P2P
- no sharing of capacity
- inefficient

Combine into hybrid WDM-TDM PON
**Bypass/removal of Local Exchange by long-reach PON**

- Major saving by reduction in (SDH) backhaul costs
- At 2.5 or 10 Gbit/s, symmetrical
- Up to 110 km, with FEC and EDC
- 500 to 1000 customer sites per amplified PON
- WDM on feeder, "λ to street corner"  
  
[D. Payne et al., ISSLS 2004]
[D. Nesset et al., ECOC 2005]

**Dynamic wavelength routing in access networks**

- Reconfigurable WDM-TDM PON: TDMA within a λ-channel of a routed WDM-PON
- Mobility and fluctuating traffic load of users
  ≡ Provides capacity-on-demand to cells
- Optimises utilisation of network resources

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**Wavelength-agile FTTH**

- flexibly allocating one or more $\lambda$-s per home, using ROADMs
- incl. protection
- colourless ONUs (using RSOA)

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**Wavelength re-allocation of a cell**

- transfer a cell to another $\lambda$-channel, as soon as it asks for more capacity than available in its present $\lambda$-channel
- considerably reduces the system blocking probability
**Impact of reconfiguration**

**Example:**
- for 8 wavelength channels @ 1.25 Gbit/s (so 10 Gbit/s in total)
- 256 users with Poisson-distributed calls, @ 63 Mbit/s or 125 Mbit/s
- using Chernoff’s upper bound approximation

≥ by using reconfiguration, the system load can significantly be increased at the same blocking probability
(e.g. doubled at $P_{\text{block}} = 10^{-3}$ for 63 Mbit/s, and more for 125 Mbit/s)

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Radio over Fibre

To increase capacity:
- Smaller cells → more antenna sites
- Higher frequencies → more complexity

Radio over Fibre

Increase capacity → big cells have to shrink

Optical Fibre
- Unlimited bandwidth
- Low loss
- Lightweight
- EM immunity

RoF techniques

- **RF Intensity modulation**
  - double sideband → carrier fading due to fibre dispersion
  - single sideband; by dual-electrode MZ modulator, or by sharp optical filter
  - high requirements on Tx bandwidth and linearity

- **Optical heterodyning**
  - two narrow-linewidth sources → e.g. by injection locking
  - self-heterodyning; e.g. with Optical Suppressed Carrier signal
  - only in SMF
  - dispersion-tolerant

- **Generating harmonics of a relatively-low frequency signal**
  - a.o. by the **Optical Frequency Multiplying technique**
  - dispersion-tolerant
  - applicable in SMF and MMF

- …
Optical Frequency Multiplying

Central Station

- low-frequency CS technology (generating harmonics of the sweep freq. by FM-IM conversion in periodic filter)
- simple antenna stations (selecting the desired harmonic)
- very pure microwave → high wireless capacity achievable by comprehensive modulation formats (such as x-QAM)
- dispersion-tolerant → for SMF and MMF

Antenna Station

-\[ f_{\text{sw}} = 6.4 \text{ GHz} \]
-\[ f_{\text{m}} = 2N \cdot f_{\text{sw}} \]

Impact of SMF chromatic dispersion

Measured delivered normalised strength of 22 GHz carrier at λ=1.55 μm, using
- Intensity-modulation, double sideband (IM-DSB); fading dips occur due to sidebands getting out of phase by fibre dispersion
- Optical Frequency Multiplying (OFM; 5th harmonic)

- OFM is tolerant against chromatic fibre dispersion, and hence suitable for link-switched routing.

[A. Ng’oma et al., Int. Microwave Symp. 2007]
[T. Koonen et al., OECC 2006]
**Dynamic capacity allocation in FWA**

- Multi-standard operation
- RAP is $\lambda$-agnostic, may handle multiple RF signals
- Link switching requires dispersion-robust RoF

![Diagram showing dynamic capacity allocation in FWA](image)

[T. Koonen et al., ECOC 2004]

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[T. Koonen et al., ECOC 2004] amjk 43
Versatile BB in-home networks

Converged in-home backbone network, integrating wired & wireless services
- reduces installation and maintenance efforts
- eases introduction and upgrading of services
- integration e.g. by WDM

POF core dimensions

chosen in POF-ALL project

PMMA POF:
atten. <45 dB / 100 m for 450 nm<\(\lambda<650\) nm (min. 8 dB / 100 m at \(\lambda=520\) nm)

PF POF:
atten. <8 dB / 100 m for 600 nm<\(\lambda<1350\) nm

300 m Ø1 mm core Si-POF:
BW \(\geq 10\) MHz
Attenuation of PMMA Ø1 mm SI-POF

Overcoming the limited BW of SI-POF

Baseband modulation formats
- 4-PAM, 8-PAM and similar amplitude-modulation formats
- refs.: Gaudino et al., POF 2005, and Breyer et al., ECOC 2008

Quadrature-like modulation formats
- QPSK, QAM-x
- benefit from high market-volume QAM technologies for wireless LAN, DVB-C, and DOCSIS cable modems
- solutions: direct-QAM, or WDM-QAM
Direct-QAM 1 Gbit/s over Ø1 mm SI-POF

- 2 channel VSG, with 2 x 40 sub-carriers, 2 MHz spaced, carrying QAM-64 and -256 signals at 1.8 MBaud
- $\lambda$ = 650 nm edge emitting DVD laser diode

WDM-QAM system

- 100Mbit/s QAM-16 $\rightarrow$ EVM < 11.4%
Radio-over-Fibre in in-house networks

- **Application:**
  - for pico-cells; range extension
  - inter-room wireless communication
  - multiple radio standards (WiFi, WiMAX, Zigbee, UWB, 60GHz, ...)
  - wired-wireless services integration (vs. all-IP)
  - smart antennas, beam steering, MIMO, ...
  - *issue:* overcoming MMF modal dispersion

- **Lack of standards ...**
  - many different techniques
  - *issue:* format-transparent signal transport

64-QAM OFM over silica GI-MMF

- **f_{sw} = 2.867 GHz**
- LD 1.3 μm
- PM
- IM
- SOA
- MZI
- VSG
- 4.4 km MMF
- VSA
- LNA
- PD
- BPF
- 17.2 GHz
- EVM = 4.8% (< 5.6% req.)

VSG = Vector Signal Generator
VSA = Vector Signal Analyzer

[A. Ng’oma et al., OFC2005]
**Inter-room μ-wave wireless communication**

- transparent for any wireless signal format
- any-to-any room communication
- multi-casting

HCC: Home Communication Controller

**Wavelength-routed RoMMF network**

- silica Ø50μm core GI-MMF
- downlink: 120 Mbit/s 64-QAM, at 23.7 GHz
- uplink: 64-QAM, at $f_s=300$ MHz, with IM/DD
- $\lambda_1=1303.8$ nm, $\lambda_2=1310.1$ nm, $\lambda_3=1314.8$ nm

RoMMF add/drop node
(MMF FBG with BW=100 GHz)

- drop and through ports

[A.M.J. Koonen et al., OFC 2008]  amjk 53

**Impact of RoF on wireless access protocols**

IEEE 802.16 (WiMAX)
- centrally scheduled MAC
- fibre delay may exceed timing boundaries of the MAC protocols and round trip delays
- time division duplex (TDD): gap between downlink (DL) burst and uplink (UL) burst, may be adapted to accommodate fibre delay

> Throughput reduction \(<1\%\) if fibre link \(<500\ m\)

![Diagram of optical link and subframes](image)

Concluding remarks (1/2)

**Re Access networks:**
- Optical fibre techniques are key for future-proof, versatile and high-capacity service provisioning in access networks.
- Fibre makes a powerful match with existing DSL, coax, and wireless customer access networks.
- For larger user areas and/or higher user numbers, a **P2MP passive network** can be more cost-effective than a P2P one.
- **TDM-PON** provides efficient capacity sharing on a P2MP passive network.
- **WDM-PON** provides P2P functionality on a P2MP passive network → easy upgrading on a per-customer base.
- A **hybrid WDM-TDM PON** enables easy network scaling, and can provide capacity-on-demand efficiently by means of **flexible wavelength routing** → optimises the exploitation of the system’s resources.
- **Radio-over-fibre techniques** can deliver high-capacity microwave signals very efficiently, in particular when using optical routing.
Concluding remarks (2/2)

Re In-building networks:

- After fibre has brought broadband capacity up to the home’s doorstep, in-home fibre networks are needed to deliver it to the user.
- An optical fibre in-home backbone enables integration of wired and wireless services, eases maintenance and upgrades.
- Large-core multimode Plastic Optical Fibre is attractive for DIY installation.
- Wired services: Quadrature Amplitude Modulation allows Gbit/s speeds over large-core MMF.
- Wireless services: Optical Frequency Multiplication allows high-capacity pico-cell communication over MMF.
- Flexible optical routing yields
  - dynamic provisioning of capacity-on-demand, and
  - reconfigurable multi-standard pico-cell wireless inter-room communication.

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