Radio over Multimode Fibre Networks

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Outline

- In-home network architecture for integrated broadband services
- Radio-over-MMF using the Optical Frequency Multiplying technique
- OFM system experiments
- Reconfigurable Radio-over-MMF networks
- Concluding remarks
**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

→ converged in-home network on POF
Radio over Fibre

increase capacity ⇒
big cells have to shrink

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

Optical Fibre
Unlimited bandwidth
Low loss
Light weight
EM immunity

Radio over Fibre

amjk 4
Radio over multimode fibre

“Optical Frequency Multiplying”

- low-cost technology
- simple antenna stations
- very pure microwave → high wireless capacity
- dispersion-tolerant → for SMF and MMF

[A.M.J. Koonen, Patent NL 1019047]
[M. Garcia Larrode et al., EL 2006]
OFM system analysis

- Monochromatic laser, optical frequency $\omega_0$ sinusoidally swept over range $2\beta \cdot \omega_{sw}$ with sweep freq. $\omega_{sw}$
- Periodic bandpass filtering before the fibre (is equivalent to filtering after the fibre)
- MZI with Free Spectral Range $\Delta \Omega_{FSR} = 2\pi / \tau$, locked to laser freq. $\omega_0$
- Neglecting fibre dispersion, photodiode output signal

$$i(t) = I_0 \cdot \left\{ 1 + \cos\left[2\beta \cdot \sin\left(\frac{1}{2}\omega_{sw}\tau\right)\cdot \cos(\omega_{sw}(t - \frac{1}{2}\tau)) + \omega_0\tau\right] \right\}$$

containing even harmonic frequency components at $2k \cdot \omega_{sw}$ with relative amplitude

$$\cos(\omega_0\tau) \cdot J_{2k}\left(2\beta \cdot \sin\left(\frac{1}{2}\omega_{sw}\tau\right)\right)$$

and odd harmonic frequency components at $(2k+1) \cdot \omega_{sw}$ with relative amplitude

$$\sin(\omega_0\tau) \cdot J_{2k-1}\left(2\beta \cdot \sin\left(\frac{1}{2}\omega_{sw}\tau\right)\right)$$
**OFM generated microwave harmonics**

- **Assumptions:**
  - sweep freq. $f_{sw} = 2$ GHz
  - MZI FSR $\Delta \nu_{FSR} = 10$ GHz
  - at each harmonic, $\omega_0 \tau$ is optimised for max. power

- Optical FM modulation index $\beta$ to be optimised for max. power in preferred harmonic (e.g., $\beta_{opt} \approx 6.3$ for $n=6$, so for the 12 GHz harmonic)
Impact of laser linewidth

- Output signal of photodiode, assuming laser linewidth $\sqrt{(\delta \omega)^2}$, and neglecting fibre dispersion

$$i(t) = I_0 \cdot \left\{ 1 + \cos[2 \beta \sin(\frac{1}{2} \omega_{sw} \tau) \cdot \cos(\omega_{sw} (t - \frac{1}{2} \tau)) + \omega_0 \tau + \delta \omega \cdot \tau] \right\}$$

→ OFM effectively suppresses laser phase noise, provided that $\delta \omega_{rms} \cdot \tau << \pi / 2$ i.e. laser linewidth is much smaller than a quarter of the FSR of the MZI $\Delta \omega_{FSR} = \pi / 2 \tau$

→ OFM generates very pure microwave carriers
Impact of MMF modal dispersion

- MMF small signal intensity modulation transfer function due to modal dispersion, neglecting chromatic dispersion
  \[ |H_{IM}(\omega)| = \frac{\Phi_{out}(\omega)}{\Phi_{in}(\omega)} \]
  where \( \Phi_{out}(\omega) \) is the Fourier transform of the output power signal \( P_{out}(t) \) of the MMF, and \( \Phi_{in}(\omega) \) of the input power signal \( P_{in}(t) \)

- neglecting chromatic dispersion, the impulse response of an MMF is a series of delayed impulses from the individual modes
  → frequency response | \( H_{IM}(\omega) \) | shows multiple lobes

- without mode coupling: amplitudes of OFM generated harmonics can be shown to scale linearly with | \( H_{IM}(\omega) \) |
  → deploy the extended frequency response lobes of MMF (or the wide frequency response of a well-equalised graded-index MMF)

- with mode coupling: the MMF itself also contributes to the OFM process;
  → the MZI contribution dominates as long as its delay \( \tau \) exceeds the MMF’s differential mode delays

[A.M.J. Koonen, A. Ng’oma, Wiley 2006]
[M. Garcia Larrode, A.M.J. Koonen, JLT 2008]
Higher-order transmission lobes in GI-MMF

**Simulation**
- MMF length $L=5$ km
- Parabolic refr. index
- Core dia. 50 $\mu$m
- Full NA launching, $NA=0.2$
- Negligible mode mixing
- Monochromatic source $\lambda=1.3$ $\mu$m
64-QAM experiment over silica GI-MMF

- μ-wave carrier freq. 17.2 GHz
- 64-QAM on subcarrier freq. 127 MHz
- symbol rate 20 MBaud → 120 Mbit/s
- over 4.4 km silica GI-MMF
- also over 25 km SMF @ 39.9 GHz
- multi-tone (up to 10 tones) 64-QAM operation at 18.3 GHz over the GI-MMF link shown

VSG = Vector Signal Generator
VSA = Vector Signal Analyzer

[A. Ng'oma et al., OFC2005]
Bi-directional system

Central Station

Antenna Station

- freq.-division duplex
- upstream: TDMA, or SCMA, incl. MAC protocol
**Bi-directional OFM link**

- Remote LO delivery
- Low cost uplink

### DL: 64-QAM, 24Mbit/s, at 5.8 GHz; $f_{sc\_DL}=200\text{MHz}$
- $f_{LO}=6 \text{ GHz}$
- 4.4 km silica GI-MMF

### UL: 64-QAM, 24Mbit/s, at $f_{IF\_UL}=200\text{MHz}$

[M. Garcia Larrode et al, IEEE PTL 2006]
Bi-dir. 16-QAM experiment over GI-POF

- downstream and upstream link: 100m 50µm core GI-POF
- PD BW=25 GHz, 50µm core MMF
- λ_{down} = 1316 nm
- sweep freq. f_{sw} = 2.867 GHz
- μ-wave carrier freq. 17.2 GHz (6th harmonic)
- subcarrier freq. 300 MHz
- symbol rate 25 MBaud → 100 Mbit/s

[A. Ng'oma et al., AP-MWP 2007]

Constellation diagram
EVM=4.8% (<5.6%)
Inter-room $\mu$-wave wireless communication

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

HCC: Home Communication Controller
Wavelength-routed RoMMF network

- Downlink: 120 Mbit/s 64-QAM, at 23.7 GHz
- Uplink: 64-QAM, at $f_{IF}=300$ 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

[M. Garcia Larrode, A.M.J. Koonen, Trans. MTT 2008]
Concluding remarks

- Future-proof, versatile and high-capacity service provisioning of multiple services in in-home networks can efficiently be done using silica or polymer multimode fibre.

- Radio-over-fibre facilitates the overlay of wireless communication services in a wired infrastructure, and the convergence of wirebound and wireless services in In-Home networks.

- With the Optical Frequency Multiplying technique microwave radio signals with high spectral purity and high capacity can be generated, and transported over dispersive multimode (and single-mode) fibre links.

- In combination with flexible wavelength routing, reconfigurable multi-standard wireless pico-cell LANs can be created.
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