Millimetre wave technology for multi-gigabit mobile networks

NMI R&D Workshop on Devices, Sensors and Systems for Flexible RF Communications

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Millimetre wave technology for multi-gigabit mobile networks

- Introduction to Filtronic
- Mobile backhaul market and use cases
- Spectrum - Why mmWave?
- Design & Technology
- Product examples
About Filtronic

- Filtronic was established 1977 currently ~200 employees

- World leader in the design and manufacture of a broad range of customised RF, microwave and millimetre-wave components and subsystems.

- Two Business Units:
  - Filtronic Wireless designs and manufactures RF filters, combiners, TMAs, microwave subsystems and antennas for the mobile telecommunications industry, focusing on equipment for OEMs and network operators. HQ in Leeds with design centres in US and Sweden. Manufacturing is carried out in Suzhou, China
  - Filtronic Broadband designs and manufactures 60 to 90GHz millimetre-wave products for mobile broadband backhaul, defence applications as well as providing build to print manufacturing at its state of the art, highly automated facility in Sedgefield Co Durham

- Filtronic has demonstrated world class product quality and reliability, with over 500,000 transceiver modules and 700,000 filter products successfully deployed in the field.

- FBL is a device agnostic supplier of mmWave transceivers to OEMs offering high specification, competitively priced modules that reduce customers time to market

- We brings value to the semiconductor suppliers and OEM customers by acting as a technology enabler

- Our target customers are focused on supplying system level products to operators and have retreated from transceiver design and manufacture
Manufacturing Capability

- Proven track record designing, manufacturing and testing carrier grade mmW products – for multiple telecoms OEMs
- 20k mm Wave modules (75% E band) shipped to date making Filtronic largest independent mm-Wave transceiver manufacturer, in the World.
- Manufacturing clean rooms with multiple automated production lines
- Epoxy dispense
- Die & component placement
- Wire bonding
  - Auto
  - Manual
- Automated test to >90GHz
- Data management
- Supply chain management
- All manufacturing in line with MIL-STD-883
- ISO9001 certified
mm-Wave Test Solutions

High Investment in mm-Wave test equipment

High speed production test systems to 90GHz
- Automated measurement and calibration of Tx Power and Rx Gain
- Two tone IMD 3 on Tx and Rx
- Noise Figure
- Rx Gain
- Calibration for LO cancellation and sideband suppression
- Return Loss
- P1dB
- Gain Flatness
- All parameters can be tested over temperature.

On wafer test to 110GHz
- NF, IMD3, Power, s-parameters
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Market drivers in Mobile Telecoms

Growth in traffic to date

3,500

Total monthly traffic (PetaBytes)

Q2 2010

Q1 2015

Forecast growth in traffic to 2020

Global mobile traffic (monthly ExaBytes)

Q4 2010, traffic generated for mobile data is twice that for voice

2X

10X

80% of mobile data traffic will be from smartphones by the end of 2020

“Total mobile video traffic over the next 6 years will be more than 22 times that of the last 6"
Basic microwave backhaul

"....... the **backhaul** portion of the network comprises the intermediate links between the **core network**, or **backbone network** and the small subnetworks at the "edge" of the entire hierarchical network".

- Cell-phones communicate with base-station antennas at the BTS (Base Station) over 3G / 4G networks

- Microwave or mmWave point-to-point links employed to **backhaul** the consolidated voice & video data to the core fibre network at the Fibre Access Point

- mmWave links, such as E-band, become increasingly important in LTE/4G networks in dense urban areas where the demand for higher capacity arises due to increasing number of users wanting data rich applications & video

www.filtronic.com
Typically costs between £30,000 and £80,000 per km to lay new fibre. Often impossible to lay new fibre where it is needed.
Multiple use cases

• Macro-cell backhaul – existing and new cells
  • Per site capacity: ~2Gbps
  • Link latency: <1ms
  • Range: <5km
  • PtP LOS

• Small-cell mobile backhaul Macro-to-street, multi-hop
  • Per site capacity: ~1Gbps
  • Link latency: <1ms
  • Range: <500m.
  • PtP/PtMP/mesh LOS/nLOS/NLOS
  • Auto-alignment / Appropriate form factor

• Macro-cell Fronthaul Mobile network upgrade, expansion
  • Capacity: ~18.4-58.9Gbps or ~8.0-24.3Gbps (w/ ORI compression)
  • BBU-RRU latency: <100us
  • Auto-alignment (w.r.t. relatively long ranges)

• Small Cell Front haul Macro-to-street, multi-hop
  • Capacity: ~2.4-9.8Gbps or ~1.0-4.1Gbps (w/ ORI compression)
  • BBU-RRU latency: <100us
  • Auto-alignment / Appropriate form factor

Source: D Siomos, 1st Official ETSI mWT ISG Workshop@LAYER123 Packet Microwave & Mobile Backhaul Forum
millimetre wave applications and use cases, 21st of September 2015, London, UK
Use cases continued

• Wireless to the Home
  • ~1Gbps 100m

• Wireless to the cabinet
  • ~10Gbps 1 to 3km

• Temporary Infrastructure Special events, public safety
  • Uncompressed video 1.485 Gbps

• Business to business
  • To 100s of Mbps 10Gbps 1 to 3 km

• CCTV Backhaul
  • Few hundred Mbps - <1km

• UAV links – military mobile hotspot
  • ~10Gbps, >15km

Source: D Siomos, 1st Official ETSI mWT ISG Workshop@LAYER123 Packet Microwave & Mobile Backhaul Forum millimetre wave applications and use cases, 21st of September 2015, London, UK
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Pressure on spectrum from 5G mobile access

- The mobile industry is now paving the way towards the standardization of the fifth generation of mobile telecommunications technology. 5G services intend to offer higher efficiency and significantly faster mobile data services.

- Some of the key targets for 5G are sub-1 ms latency and over 1 Gbps DL speed, while the data rate of 10 Gbps is the minimum theoretical upper limit speed discussed for 5G.

- To achieve the target of 10Gbits peak download capacity requires several GHz of contiguous spectrum – (>1GHz per operator)

- Spectrum above 6 GHz now under consideration for 5G to provide wider bandwidth channels to support higher volume data communication to wireless devices.

- Ofcom commissioned a study which identified top 5 bands as candidates for 5G – all mm Wave

- Ofcom subsequently also identified lower frequency bands although these may not offer sufficient bandwidth

- Similar work ongoing with ITU and FCC

Source; Ofcom 5G and Future Technologies presentations: http://stakeholders.ofcom.org.uk/spectrum/spectrum-events/5g-future-technology/
5G mobile access will create challenges for mobile backhaul

• Potential threat to existing fixed service bands - the allocation of bands above 6GHz for 5G (deployments after 2020), can endanger the capability of operators to properly operate backhaul networks for 3 and 4G

“All discussions about allocation of spectrum for 5G must consider the needs of the operators for backhaul, current (3 and 4G) and future (5G)”*

“The allocation of spectrum for 5G cannot be separated by the allocation of sufficient and suitable spectrum to deploy the backhaul network” *

* Renato Lombardi – ETSI mWT ISG Chairman.
• In the traditional bands there are a number of narrow channels spread between 6 and 42GHz. The total bandwidth available for mobile backhaul below 42GHz is just 15GHz. This now heavily used and expensive licences are required to operate in these bands.

• In contrast, the millimetre wave bands will provide an additional 21GHz of bandwidth in large chunks allowing very high data rates to be achieved.
Below 95GHz

- <26 GHz and 38 GHz highly congested - often used for current mobile backhaul
- v-band (57 to 64, 64 to 66 GHz)
  - License-exempt – in many countries
  - Small Cell Backhaul, enterprises
  - TDD, FDD, in future Full Duplex
- e-band (71 to 76, 81 to 86 GHz)
  - Light license for Macro Cell Backhaul, aggregation
  - FDD, channels from 250 MHz to 2 GHz
- w-band (92 to 95 GHz)
  - Too small to be significant when compared with v-band and e-band
  - TTD, not feasible Go-Return in 3 GHz at 93 GHz

E-band appears the one RF band capable of allowing transmission of the required capacities over few kilometers at reasonable cost and should be the ideal solution for backhaul of first aggregation signals (backhauling of macro-cells / suburban areas etc).
Above 95GHz

- Future mobile networks beyond 2020 need to support vast applications and services with explosive capacity requirements of 1000’s times the current capacity. This will have impact on transport network for backhaul, midhaul and fronthaul applications requiring N x 10Gbps capacity and a massive amount of spectrum.

- Point to Point radio will continue to be a major mobile backhaul medium, connecting around 50 percent of all radio sites in 2020 and beyond. It is estimated that many times the current capacity provided by the band in 71 -76 and 81 – 86 GHz will be needed to support future mobile networks.

- Long term requirements for backhaul of 5G and mid term for fronthaul require capacities that can be transmitted only by allocating very large portion of spectrum above 90 GHz.

- New ECC Recommendation for radio frequency channel arrangements for fixed service systems operating in the frequency blocks already allocated to fixed services in the bands 92 – 94 GHz, 94.1 – 100 GHz, 102 – 109.5 GHz and 111.8 – 114.5 GHz. 141 – 148.5, 151-164 and 167 – 174.7 GHz.

Source: proposal for Proposal for New WI Recommendation to ECC SE19 at 71st Meeting, 8-9 September 2015
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E Band Outdoor unit

- Baseband Clamshell
- Baseband PCB: Modem, Power supply and switch
- Ethernet and Power Connections
- RF PCB and diplexer
- RF Subassembly / Clamshell
- Antenna Mounting Surface
E Band Transceiver Block Diagram

Key Performance Parameters

- Tx and Rx Linearity Mask compliance SNR
- Phase Noise Modulation order/SNR
- Noise Figure – System Gain
- Tx Power – System Gain
RF Analog Semiconductor Technologies Trends

- Compound semiconductors are essential for high performance systems
- Highly integrated GaAs chip sets available now – relatively low initial investment makes these well suited to backhaul volumes
- Si based technologies offer a good solution for short reach systems but demand high volumes to justify initial investment
- SiGe /GaAs combinations achieving usable levels of Macro cell performance.
- Phase noise currently a major limitation for fully integrated SiGe – Use of external low noise VCO required For reliable operation with high order modulation,
Semiconductor technology status

- **GaAs**
  - Highly integrated single chip receivers and medium power transmitters available from several vendors
  - Power amplifiers to 30dBm demonstrated with commercial 0.1um pHEMT Foundry (WIN)
  - GaAs mHemt processes have demonstrated 2dB NF in E band (BAe 50nm mHEMT) LNAs expected to go into production in 2016

- **InP** <2.5dB NF demonstrated with 0.1um InP HEMT (Northrop Grumman)

- **GaN** PAs with Psat >30dBm to 100GHz demonstrated (HRL 0.14um GaN on SiC)

- **InGaP/GaAs** HBT – Low phase noise VCOs -93dBC/Hz at 1MHz after multiplication to 86GHz

- **SiGe** First generation (130nm, ~250GHz ft) highly integrated chips available. Power 12dBm to 18dBm (Psat), Noise figure 8 dB to 11dB. (up-to 16dB over temperature). Phase noise ~ -83 dBC/Hz. Well suited to 60GHz small cell and WiGig

- **BiCMOS** – PAs reported up to 20dBm on 40nmCMOS. NF similar to SiGe. mmWave CMOS Still at development phase – very high initial investment so will require very high volume application.
mmWave assembly

- Packaged mmWave die to allow SMT assembly are appearing in form of SIP/ MCMs, chip scale BGAs and flip chip die, however, any form of packaging will impact the performance – up to 2dB loss in typical plastic BGA. Also concerns over thermal impedance and reliability of flip chip PAs.

- FBL has in house automatic die attach and wire bond capability to allow direct integration into microwave assemblies to achieve the highest level of performance without the need for the addition complexity and cost of a packaging.

- Hybrid construction gives ability to mix and match technologies e.g. Quartz filters and printed micro strip components – plus SMT components.
Die & Component Placement

- Fully automated component placement equipment enables tightly controlled, accurate and repeatable die placement
- Vacuum picked from waffle pack or reels
- X/Y placement accuracy +/- 12 microns
- Automated recognition system for alignment of fiducials and components
Palomar Ball bonders

- 2 machines onsite
- Between 10 and 11 years of production.
- Using force, heat, ultrasonic energy and time to create intermetallic bonds.
- Using 25-33 micron 99.99% pure gold (higher spec than 24 carat).
- 2-3 wires per second.
- Deep access bonding allows bonding over surface mounted components without collision.
Epoxy Dispense

- Fully automated epoxy dispense equipment provides tightly controlled, accurate and repeatable epoxy dispense. Filtronic has significant experience of dispensing different epoxy types, in optimised patterns
- Deep access epoxy dispense capability
- Automated camera recognition system for accurate alignment and epoxy dispense
- Conveyor system fitted for continuous production flow
Assembly Challenges 1

Manual wire / ribbon bonding

MMIC to MMIC connections
Assembly Challenges 2

Typical tolerances in the conventional approach:
1. The separation between adjacent devices on the semiconductor wafer is typically 70µm, so the MMIC bond pad could be 35µm further away than nominal from the chip edge and 35µm closer to the opposite chip edge.
2. The accuracy of cutting the pocket in the main circuit board, relative to the main circuit board track is ±25µm.
3. MMIC placement accuracy in the electronic assembly is typically ±20µm.

Therefore, the overall variation of pad positions is ±80µm.
Assembly Challenges 3

Bond compensation

Nominal case: 300um long

Possible to apply compensation but still subject to assembly tolerance and variations in bond length.
**Solution**

Replace inductive wire with a transmission line whose match to the components being connected is independent of its length. The line length accommodates the biggest gap expected. Such an interconnect must take into account the different capabilities of the MMIC and PCB technologies. Minimum track/gap dimensions allowed for PCBs are ~100µm.

CoPlanar Waveguide transmission line

Since the pattern is just on one side:
- it is cheap
- tracks can be seen from opposite side to allow alignment
- impedance can be maintained with different Signal/Ground gaps to accommodate the different technologies being connected.
Assembly Process for new interconnect

- Requires no additional process steps in MMIC fabrication Therefore applicable to any MMIC
- Maintains optimum thermal connection to base plate – essential for PA assemblies
Demonstration of improvement of new interconnect over conventional method

s-parameters of MMIC- Interconnect – PCB – Interconnect – MMIC measured

s21(dB) of the complete structure showing lower loss with the new interconnect

Requires no additional process steps in MMIC fabrication
Therefore applicable to any MMIC
Diplexers - Integration into E-band Transceiver Module

Transceiver “A” transmits and “B” receives in a channel within 71-76GHz at the same time that Transceiver “B” transmits and “A” receives in a channel within 81-86GHz.

A transmits over 71.875 – 72.125GHz
B transmits over 81.875 – 82.125GHz

Filtronic E-band transceiver module with integrated diplexer

Modem interface connector

Filtronic E-band diplexer – designed for transceiver integration

WR-12 Antenna port
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Filtronics Transceivers

Filtronics Transceivers
- Direct Up and Down conversion
- In-house designed GaAs chip set
- Integrated diplexers
- Micro controlled Tx Power setting and RSSI & PLL and VCO with centre frequency set in 32.25MHz steps
- Low Phase noise -112dBm/Hz
- 1.5GHz BB bandwidth
- Fully integrated requiring just a single connection to the modem for Tx and Rx baseband signals, power supplies and SPI control.
- Contains VCOs, PLL and a microcontroller to set operating frequency and transmit power. Automatic Rx gain control is incorporated to adjust the Rx gain to accommodate receive signals over >65dB dynamic range.

Filtronics chip set comprises
- Up converter - direct conversion
- Variable Gain PAs (25dBm Psat)
- Multipliers X2 and X3
- Integrated LNA/LOA/downconverter
- Low noise LNA
- VVA

Theseus
- Second generation transceiver
- In House chip set
- Integrated surface mount diplexer
- Capable of operating at modulations levels up to 256QAM
- 1GHz BB bandwidth
- 3.2Gbps with transmit powers up to 12dBm in 500 MHz channel,
- 1.6Gbps 16 QAM 17dBm
- High Gain Rx with AGC

Orpheus
- Filtronics Third Generation transceiver
- In-house designed GaAs chip set
- Integrated diplexer
- 1.5GHz BB bandwidth
- Capable of operating at modulations levels up to 256QAM
- 4.5Gbps in 750 MHz channel
**E-Band Product Roadmap**

**Proteus**
- EOL Standard power E-band product
- Supplied in significant volumes to major OEMs

**Theseus**
- High power E-band product
- FBL GaAs PA and HPA
- Qualified and in production
- Cost reduction vs. Proteus
- Supplied in significant volumes to major OEMs
- Low Phase Noise
- 256QAM capability
- Single connector Modem interface; BB, Power and control.

**Orpheus**
- Small form factor
- Integrated diplexer
- Internal low phase noise VCOs
- Fully calibrated Tx and Rx chains including control board with on-board micro for
  - Tx power control loops,
  - Temperature correction
  - Alarms
  - Rx base band circuitry
  - Voltage regulation and MMIC bias circuitry
- Significant cost reduction vs. Theseus
- Common interface with Theseus
- Psat 25dBm
- 256QAM

**Future E band product enhancements**
- Higher transmit power (>30dBm)
- Lower Noise Figure (<4dB)
- Higher integration Integrated Antennas and OMTs
- Small Size and Weight - airborne applications

**Perseus mmW Module**
- Low cost form factor mmW only module
- Optional integrated diplexer
- Further cost reduction vs. Orpheus
- Direct customer control of Rx and Tx gain
- Solder free surface mount technology for simplest integration
- Rx compatible with direct conversion and IF based systems

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E Band High Performance Reference Designs

- Filtronic Transceivers
- Escape Communications Modem

Performance demonstrated 2015
- Adaptive modulation 4QAM to 256QAM
- 3.2 Gbps
- 256 QAM (Adaptive 4QAM to 256QAM)
- 500 MHz Channels

Wide Band version under development
- Adaptive modulation 4QAM to 256QAM
- 1.5GHz Channels
- 4.55Gbps in 750MHz channel demonstrated to date
- >10Gbps capability with XPIC
E Band Reference Design Performance

- I/Q Constellation of 3.18Gbps link using 256 QAM with a 500MHz channel BW at 85GHz.
- SNR >36dB \(\sim 512\) QAM at \(10^{-6}\) BER

![BER vs C/N for different modulations](image-url)
E-band Link Range

Gain = $\frac{\pi^2 d^2}{\lambda^2 \epsilon}$

Free space loss = $20 \log(4\pi d/\lambda)$

131dB for d=1km, 145dB for d=5km

Gain = 43dBi

NF = 7dB

Whole North America <50mm/hour for >99.95% of year
E band Antennas give 6dB more system gain than 40GHz
Filtronic Broadband mm-Wave and Microwave Capability

Full custom design and volume manufacturing and test services for

- E Band transceivers 71 to 86GHz
- V band transceivers 57 to 64GHz
- ODU ready E band link reference designs
- Waveguide Filters, Diplexers and OMTs 6GHz to 110GHz
- GaN High power amplifiers 6 to 11 GHz
- Multichip Modules 6 to 24GHz
Thank you for listening