mm Wavelength Communication Systems

Stan Skafidas
Email: stan.skafidas@nicta.com.au
National ICT Australia Limited
Dept of Electrical and Electronic Engineering
University of Melbourne
Talk Outline

- mm wavelength wireless communication systems
- Advantages of mm wavelength systems
- Applications of mm wavelength systems
- Challenges in implementing mm wavelength systems
  - Channel/propagation properties
  - Transceiver design issues
  - Device modelling and characterization
New spectrum being made available worldwide

- **US**
  - 57-64 GHz is unlicensed in the US (largest unlicensed block ever allocated by FCC).
  - 71-76 and 81-86 GHz will be allocated in the US, likely by the end of this year
- **Canada**
  - 59-64 GHz is unlicensed in Canada
  - 57-59 GHz will be added in the future
- **Japan**
  - 59-66 GHz is unlicensed in Japan; 55-59 GHz band available by license
- **UK**
  - 64-66 GHz was recently allocated in the UK.
Advantages of mm Wavelength Wireless

- Large Amounts of Bandwidth
  - High Data Rates
- mm Wavelengths allow very small high gain arrays
  - High Directivity Antenna at the Access point
  - High Directivity Antenna at the CPE
- High Component On Chip Integration Possible
  - Filters
  - Passives (Inductors & Capacitors)
  - Antennas and Phase Arrays
mm Wavelength (60GHz) Applications

- WiLAN
  - 1Gbps to the desktop
- WiMAX
  - 60GHz (70Mbps)
- Bridge
  - Fiber Extension
  - Backhaul
- Gigabit Car to Pole
- Gigabit Mobile
mm Wavelength Channel Properties

- At 60 GHz there is much more free space loss than at 2 or 5 GHz.
  - Friis Equation – Quarter Wavelength Dipole - (68dB @ 1m)
  - Oxygen Absorption (15dB/km)
mm Wavelength Channel Properties

• Significant Signal Drop Out
  – In order to achieve requisite data rate a given distances high gain antennas need to be used
  – High gain antennas are susceptible to obstruction
    • Human is essential a bag/cylinder of salt water
    • Measurements show that a person can easily create a 25dB fade

• Doppler can be significant
  – Person moving at 3km/h at 60GHz has the same doppler offset as a car traveling at 200km/h at 900MHz
  – Environment is significantly more dynamic than that at lower frequencies
Channel Propagation

- Propagation is significantly more LOS than 2.4GHz
  - Signal is received in 2-3 clusters in time
  - Impulse response length can be quite long (60ns)
    - Has significant implications on modulation schemes
- Received signal is also received in certain clusters
  - Not spatially diffuse
  - MIMO schemes not applicable
Channel Model

- SV Model

\[ h(t) = \sum_{l=0}^{L} \sum_{k=0}^{K} \alpha_{k,l} \delta(t - T_l - \tau_{k,l}) \]

- \( T_l \) = the arrival time of the first path of the \( l \)-th cluster;
- \( \tau_{k,l} \) = the delay of the \( k \)-the path within the \( l \)-th cluster relative to the first path arrival time, \( T_l \);
- \( \Lambda \) = cluster arrival rate;
- \( \lambda \) = ray arrival rate, i.e., the arrival rate of path within each cluster.
Propagation Channel Impulse Response

- Impulse Response Data Removed
- Contact Authors for Data
Channel Measurements

- Measured Data Removed
- Contact Authors for Data
Implementation of mm Wavelength Systems

• mm wavelength systems have been built before
  - Systems have generally been point to point
  - System have been generally very expensive (>50K)
  - Challenge is building: cheap, reliable, multipoint gigabit/s system

• 60GHz CMOS Radio Transceiver
  - CMOS (compared to SiGe GaAS InP)
    • Is cheaper
    • Has lower electron mobility
    • Lower breakdown voltage
    • Harder to build high Q passives
  - Lots of Challenging problems to be solved
    • CMOS transistor models inaccurate (BSIM 3 or 4)
    • Significant Parasitic Losses of Passives
  - Lower Power Outputs
    • Smaller geometries have smaller voltages

• Lots of research problems
Receiver Structures

- **Super Heterodyne**
  - 2 Mixing Stages
    - Nonlinearity
    - Phase Noise
    - Cost
  - 2 Bandpass Filters
    - SAW Filters
    - Cost
  - 2 VCOs
    - Might be necessary if one VCO cannot be built with requisite performance characteristics
      - VCO performance limited inductor performance and transistor fmax
Receiver Structures

- **Direct Conversion**
  - One mixing stage
  - 1 Local Oscillator/VCO
  - No SAW filters required
- **Difficult to build VCO**
  - High Phase noise of VCO
- **Reverse isolation of mixer hard to achieve**
  - Conduction through bulk
  - DC Offset problem
DC Offset

- DC OFFSET PROBLEM

- Static offset due to LO leakage, Circuit mismatches
- Dynamic offset due to antenna reflection and second order intermodulation
• Voltage Controlled Oscillator used to set the channel frequency
VCO Phase Noise

- Low value of Q of inductor introduces more phase noise

\[ |H(s)| = \frac{Q_p}{\sqrt{2}} \quad \text{for} \quad \omega = \omega_p \]

carrier-to-noise ratio = \( kQ_L \left( \frac{V_{\text{signal}}}{V_{\text{noise}}} \right)^2 \left( \frac{\Delta f^2}{f_c^2} \right) \)
Effects of Phase Noise

16-ary QAM constellation without distortion

Add Phase noise and Frequency offset
Memoryless Nonlinearity

To model radio frequency (RF) impairments to a signal at the receiver.
- Cubic polynomial
- Hyperbolic tangent
- Saleh model
- Ghorbani model
- Rapp model
Effects of Memoryless Nonlinearity (Saleh model)

16-ary QAM constellation without distortion

A scatter plot of the same signal after it passes through the Memoryless Nonlinearity block (Saleh Model)
Transmit PSD

- High degree of linearity required for PA
  - need low PAR modulation schemes
  - Clipping causes out of band emissions
  - FCC Requirements
    - EIRP <-15dBm (40-200)GHz
    - EIRP <-77dBm (<40) GHz
Component Modelling

- In order to do design need to model and characterize the process/transistors/passives
- Pads and other parasitic effects make model extraction very difficult
  - Unstable
  - Very difficult to extract models
Nicta 63x8p25 (SOI) RF Transistor
Nicta 3x8p25 (SOI) RF Transistor
MOSFET RESPONSE

\[ f_t = \frac{1}{2\pi} \frac{g_m}{c_{gg} + c_{gso} + c_{gdo} + c_{par}} \rightarrow \frac{1}{2\pi} \frac{v_{sat}}{L_g} \]

\[ f_{\text{max}} \approx \frac{f_t}{2\sqrt{(R_g + R_i)(g_{ds} + 2\pi f_t c_{gdo})}} \]

- \( g_m \) = transconductance
- \( C_{gg} \) = gate-channel capacitance
- \( C_{gdo} \) = gate-drain overlap capacitance
- \( C_{gso} \) = gate-source overlap capacitance
- \( C_{par} \) = gate parasitic capacitance
- \( V_{sat} \) = carrier saturation velocity
- \( L_g \) = effective gate length
- \( R_g \) = gate resistance
- \( R_i \) = equivalent input resistance for non-quasi static effect
- \( g_{ds} \) = output conductance
Lab Setup
Small Signal Transistor Model

\[ Y_{11} = \frac{r_i C_{gs} \omega^2}{1 + \omega^2 C_{gs}^2 r_i^2} + j \omega \left( \frac{C_{gs}}{1 + \omega^2 C_{gs}^2 r_i^2} + C_{gd} \right) \]

\[ Y_{12} = -j \omega C_{gd} \]

\[ Y_{21} = \frac{g_m e^{-j \omega \tau}}{1 + j r_i C_{gs} \omega} - j \omega C_{gd} \]

\[ Y_{22} = g_d + j \omega \left( C_{ds} + C_{gd} \right) \]
Equivalent Circuit Model

Equivalent circuit of the impedance model of the test-fixture
Innovative Antenna Designs

- Antenna Fabrication in Package
- Small Package
- Lost Cost
- Beam forming elements included on chip
Inductor
Medium Frequency Models for Inductor

- Medium Frequency Inductor Model
- Not accurate at high frequencies
- Need Distributed Models to accurately model inductor characteristics
The imagination driving Australia's ICT future.

Capacitor

- Capacitor
Conclusion

• Ability to provide gigabit speeds
• Lots of challenging problems that need to be solved
  – Baseband
  – Devices
  – Integrated Components