5G Communications with Glass Embedding and Fanout

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Strategic Needs

Increasing automotive, IoT, Smart City communication needs:
• Higher automation levels,
• Avalanche of wireless communication traffic volume and massive growth
• 10-100x higher data rates 4G LTE

Enable the functionality of:
▪ Enhanced Cognitive Intelligence
▪ Automated driving with safety
▪ Intelligent navigation
▪ In-car smartphone-like infotainment (Information Society on the road)
▪ Predictive Maintenance
▪ Digitalization of transport and logistics (e.g. Intelligent Transportation Systems (ITS))
Strategic Needs II

Vehicle-to-Everything (V2X): Any communication involving a vehicle as a source or destination of a message:
- Vehicle-to-Vehicle (V2V)
- Vehicle-to-Infrastructure (V2I)
- Vehicle-to-Network (V2N)
- Vehicle-to-Pedestrian (V2P)
- Intersection Collision Risk Warning
- Road hazard warnings (road works, car breakdown, weather conditions, etc.)
- Approaching emergency vehicle warning
- Pre-/Post-Crash
- Electronic Emergency Brake Warning
- GLOSA – Green Light Optimal Speed Advisory
- Energy-efficient intersection
- Motorcycle approaching information
- In-vehicle signage
- Red light violation warning
- Traffic jam ahead warning
5G networks

**Defining characteristics**

- Cellular network
- 75dBm EIRP FCC limitation (compared to 36 dBm for UHF RFID readers)
- Small cells (300-500m radius)
- Mm-wave
- **Beamforming**
- Spatial multiplexing
Internet of Things – including RFID carrier variants
P.I.R.E.A.S. Testbed
(Prototypes of Integrated RF-Enabled Agile Systems)

Network
- RFID/Sensors
- Network/Tracking
- EMI/EMC Suppression

Module
- Integrated Module System-on-Package
- 5G / RF

System
- Automotive, Biomedical, and Security
- Multistandard HF, VHF, RF, mmW
- Low-cost Materials, Printing Technology
- Sensors, Power Sources

Components
- Antennas, IC’s
- Interconnects, Passives
GT Research Objectives

Explore novel designs, materials, processes and 3D packaging structures and RF components to build 5G-enabled modules that accommodate V2X, IoT, SS, SC applications with superiority over LTCC and organic packages in terms of:

1) Performance,
2) Miniaturization
3) Reliability
4) Cost
5) Integrability (e.g., transparent)
6) IoT compatibility
7) Broadband/multiband (e.g., 5.9GHz/mmW) operability
Mm-Wave Systems and Packaging with Printing

**Materials:**
- Photoactive resins, thermoplastics, ceramic pastes, conductive adhesives

**3D Printing**
- Dielectric lenses
- Encapsulations
- Die-embedded leadframes

**Inkjet Printing**
- 3D interconnects
- RF substrates
- Die attach
Printed mm-Wave Antennas

- Millimeter-wave (mm-wave) regime is emerging for automotive radar and 5G wireless
- Use printing to fabricate antennas in a low-cost and robust post-process fashion

**Proximity-Coupled Patch Arrays**
- Dielectric spacer printed to separate feed lines and patch resonators
- Exhibits high broadside gain for mm-wave applications in 24.5 GHz ISM

**Yagi-Uda Antenna Arrays**
- Dielectric substrate printed to convert microstrip feed to slot-line
- High end-fire gain achieved with multi-director configurations

**On-Package Antenna Integration**
- 30 GHz patch antenna printed directly onto chip molding
- Printed ground plane provides isolation from IC package
- Can be integrated with wireless IC through aperture coupling or through-package-vias (TPV)
3D Printed Antennas and Systems

• Previous work utilizing basic FDM printers and direct write systems.
• Extremely low cost, utilizing Direct Write for metallization and FDM for dielectrics

Microfluidic Reconfigurable Microfluidic SIW
• Resonate frequency based off dielectric constant within microfluidic channels
• FDM Printed with thermoplastic polyurethane (TPU) and PLA

Strain Sensing Hollow Cube
• Thin lines (200 μm) of silo-ECA (electrically conductive adhesive) stretchable conductor printed on
• ~80 MHz change based on strain due to hollow interior topology of the cube.

Hybrid Manufactured Vivaldi Antenna Array
• Utilizes subtractive and additive manufacturing
• ABS/Copper Tape (subtractive)/Dupont CB028 Silver Paste
• 2.8-8 GHz operational frequency
Inkjet-Printed 3D mm-Wave Interconnects

- Efficient interconnects essential for system-on-package (SoP) solutions
- Use inkjet printing to realize 3D mm-wave interconnects between IC die and packaging substrate

![Diagram of inkjet-printed interconnects between IC die and packaging substrate]

- Loss at 40 GHz: 0.6–0.8 dB/mm
- Inductance half of typical wirebond (0.4 nH/mm)
Mm-Wave SoP Antenna Integration

- Use inkjet-printed interconnects to **directly interface** IC die with SoP antenna
- Minimize system complexity, interconnect length, and transmission losses

- Wideband CPW-fed bowtie antenna covering 23–40 GHz using glass as RF substrate
- Multilayer printing allows for **isolation from packaging substrate** in future efforts
## Additive vs Subtractive Fabrication

<table>
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<th>Technology</th>
<th>Feature Size (µm)</th>
<th>Multi-Layer</th>
<th>Cost</th>
<th>Speed</th>
<th>Waste</th>
<th>Area (m²)</th>
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<td>No</td>
<td>Low</td>
<td>Slow</td>
<td>High (Dust)</td>
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<td>Laser Ablation</td>
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<td>0.01</td>
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<tr>
<td>Gravure Printing</td>
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<td>High</td>
<td>Fast</td>
<td>Medium (Excess Ink)</td>
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<tr>
<td>Screen Printing</td>
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<td>Low</td>
<td>Fast</td>
<td>Negligible</td>
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Inkjet-Printed On-Package 30 GHz Antenna

Fig. 4. Simulated (a) YZ and (b) XZ normalized radiation pattern cuts.
Van-Atta reflect-arrays: Ultra-low-power “A+S” Wireless Nodes with 1km+ Ranges

- Unique combination of properties
  - Arbitrarily high RCS (fully scalable)
  - Largely angle independent monostatic response
  - Cross-polarized response

- Reader system consequences
  - High frequency operable (unused bands)
  - High gain, compact, reader antennas (long range)
  - Narrow beamwidth reader antennas (clutter isolation)

- Operational advantages
  - Unprecedented (angle independent) reading range (1km+)
  - Extremely high clutter-induced-interference isolation
  - Compactness
  - Unique Authentication + Multiagent Sensing (“A+S”)
Printed mm-Wave Chip-less RFID/Humidity Sensor

- Fully printed mm-wave passive system inkjet-printed Van-Atta reflect-array, consisting of 25 patch antennas on a surface Range finder, RFID, and humidity sensor
- Over a range of 140° variation of the angle of incidence of the interrogation signal, the RCS varied only by 10 dB, even for flexed configurations
Printed, flexible, backscatter-modulation Van-Atta sensor structure

- Active backscatter-modulation Van-Atta
- All the advantages of the passive Van-Atta + non-linear response
- Enables this new structure with
  - Ultra-long-range reading capabilities (up to several kilometers)
  - Outdoor or indoor energy autonomy with solar cell:
    - Ultra-low power consumption (200uW)
  - Almost immediate integration of any of our printed gas sensors
    - Several on the same platform, in the future
Backscatter-modulation Van-Atta structure: sensing

• Printed CNT-PABS ammonia sensor was integrated
• Short ammonia sensing event was measured (as shown on the IF spectrogram)
  • Very quick response
Backscatter-modulation Van-Atta structure: Ultra-long-range (100m+)

- Sensor interrogation was demonstrated at a record range of 580m (80m+ here)
- Range is now only limited by the poor noise performance of our mm-wave signal generator
  - Range would be extended to kilometers with higher performance LO
Inkjet-Printed 2D/3D EMI/EMC Isolation Structures

- Flexible inkjet-printed metamaterial absorber on paper
- Silver nanoparticle ink
- 95% absorptivity at 9.13GHz for an angle of incidence of less than 40° and polarization insensitivity
Flexible Inkjet-Printed Microfluidics

• Small channel down to 60 um*0.8 um
• Flexible
• On virtually any substrate (e.g. glass)
• Tunable microwave structures
• Ideal for water quality monitoring and biosensing
Wireless CNT-Based Gas Sensors

• Printing of 5 to 30 layers of CNT ink
• Drying at 100°C for 10 hours, under vacuum
• Chemical functionalization of film
• Printing of electrodes with silver nanoparticle ink (SNP)
• Drying and sintering at 110°C for 3 hours
Results for rGO sensor

• Response time comparable to that of commercial sensor
• Sensitivity of 8.5% to exposure to 28 ppm of NH$_3$
• To our knowledge, highest sensitivity fully inkjet printed rGO ammonia sensor
Additively Manufactured Ambient Long-Range RF Energy Harvester


Energy Harvesting circuit to capture power from air

- **EH Circuit performance**
  - 12 µ-watts of wireless power -> 1.8V DC out
  - 17 µ-watts of wireless power -> 2.2V DC Out
  - 25 µ-watts of wireless power -> 3.3V DC out

- **EH Circuit design includes:**
  - Converts microwatts of wireless power to over 3V of DC output signal
  - No batteries - Uses Capacitor to wireless power
  - Powers up microcontroller for power management and sensing applications

Misalignment-Insensitive Highly-Efficient WPT

Source Element
TX 3D loop resonator

Load Element
RX 3D loop resonator

Provisional patent # 61/658,636
Wireless Energy Harvesting Circuit

- Converts Wireless Power in air due to cell and TV signals into usable DC
- Antenna: Converts E-field in air to RF sine wave
- RF Charge Pump: Converts RF Sine Wave and steps it up to higher DC Voltage
- Charge Tank 100uF Capacitor: Stores harvested RF Power
- Power Management Unit: Works with Microcontroller firmware to
- BATTERY-LESS

**Inkjet Printed version on paper**

**FR-4 version**

**To Microcontroller**

**Analog PMU**

**To Antenna**

**100uF Cap**

**Charge Pump**

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RF energy harvesting for on-body communication/sensing

- Wearable flexible backscattering capable on-body communication/sensing platform powered by energy harvester for two-way talk radio
Wireless Sensor Module: 904.2 MHz

- Single Layer Module Circuit printed on Paper using inkjet technology
- Integrated microcontroller and wireless transmitter operating @ 904.2 MHz
- Module can be custom programmed to operate with any kind of commercial sensor, environment & Communication requirement
- Rechargeable Li-ion battery for remote operation
- Maximum Range: 1.86 miles

Circuit + Sensor + Antenna on Paper

Antenna Radiation Pattern showing high gain

Wireless Temperature Sensor Signal sent out by module, measured by Spectrum Analyzer

Wireless Signal Strength sent out by module, measured by Spectrum Analyzer
Wireless Sensor Module: 904.5 MHz

- Double Layer Module Circuit printed on Paper using inkjet technology
- Integrated microcontroller and wireless transmitter operating @ 904.5 MHz
- Module can be custom programmed to operate with any kind of commercial sensor, environment & Communication requirement
- Rechargeable Li-ion battery for remote operation
- Maximum Range: < 8 miles
3D-Printed Antenna with Arbitrary Embedded Cavity for Directional Strain Sensing

3D antenna design – a dipole antenna

(a) 3D antenna on a hollow cube; (b) To add strain on the front and the back surfaces of the cube.
ENERGY AND BANDWIDTH EFFICIENT SENSORS

- Sensor front-ends for increased spectral efficiency
- Nanowatt-microwatt operation
- Low bias voltage 0-2V
- Can be directly interfaced to low-power microcontrollers for sensing and communication
ENERGY AND BANDWIDTH EFFICIENT SENSORS

- Wired and wireless measurements with software-defined radio receiver
- Significantly **reduced bandwidth** compared to rectangular pulses
- More than 35 dB out-of-band **suppression** compared to rectangular pulses
- Can fit more sensors in the band, or transmit higher data rates (**Gb/sec**) from single sensor/matrix of sensors
InkJet Printed MCM Prototype

• Compact module utilizing inkjet printing for next gen inkjet printed MCM packaging

• CC2520 IEEE 802.15.4/ZIGBEE RF Transceiver
• CC2592 Range Extender
• Integrated 2.4 GHz PIFA Antenna
• Liquid Crystal Polymer (LCP) Substrate
• 0402 SMD components (1x.5 mm)
Morphing (4D-Printed) Origami-Enabled Sensor Node

- Origami systems – able to **fold and reconfigure** to deploy in field and alter performance
- Shape memory polymers (SMPs) allow for reconfigurability with the influence of external stimuli (heat, current, etc)

3D Wireless Sensor Node

- Wireless energy harvesting for self-powered sensing
- Multiple antennas in cube shape allow for orientation-independent operation
- Fabricate planar foldable structure to reduce fabrication time
Printed Origami-Enabled Sensor

- 3D printing fabricates foldable cube package, inkjet printing fabricates metallic patch antennas
- SMP (TangoBlack/VeroWhite blend) hinges exposed to thermal treatment (50~60 °C) allowing for folding and shaping, holds shape when returning to ambient

Multi-Port Wireless Harvesting
3D-Printed mm-Wave Packaging

Challenges for mm-wave system packaging:

• Low-loss materials
  • Increase wireless system efficiency
  • High-frequency dielectric characterization necessary

• Miniaturization
  • Reduce package size and interconnect length
  • System-on-package (SoP) integration desired

Printing Solutions:

• Additively fabricate electronic structures
  • Reduce processing tools/steps
  • Remove high temp and pressure, less package stress on die

• High process reconfigurability
  • Short-run prototyping and mass-scale production
  • Multi-application processing with single tooling technology
3D-Printed Encapsulation

- Standard 1 mm-Thick Encapsulation
- Text and Detailing
- Lens Integration

Side View
Post-Process On-Package Printing

- Use inkjet printing to fabricate metallic structures on top of 3D-printed encapsulation
  - Decoupling capacitors
  - Antenna arrays
  - Frequency selective surfaces (FSS)

Periodic Jerusalem Cross FSS inkjet-printed onto 3D-printed encapsulation
Flexible Waveguides & Interconnects/ 3D Antenna “Tree” / 4D “Origami” Broadband Flexible FSS / Zero-Power Wearables
[to be announced in IEEE IMS 2017, June 2017]