Leveraging Quantum in Communications & Sensing Systems

A System’s Perspective

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Introduction

Dr. William Clark
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General Dynamics Mission Systems

William earned his Ph.D. in Theoretical Atomic, Molecular and Optical (AMO) physics from the University of Colorado, Department of Physics and the JILA Quantum Physics Institute in Boulder, Colorado in 1998. William has more than two decades of industry experience in Systems design, development and integration of next generation tactical and strategic communications systems, including software defined radio and networking technologies, and active and passive sensing systems. William is currently leading several Quantum R&D projects in support of Space and Intelligence Systems (SIS), Ground Systems (GS) and the Maritime and Strategic Systems (M&SS) business areas, exploring the practical use of quantum technologies for secure and covert communications, remote sensing and signal processing.
Our Vision - Quantum CONOPS

Trade Space
- Photon Types & Sources
- Photon Detectors
- Range Performance
- Data Rates
- Pure vs. Mixed Quantum & Classical Channels
- …

Q-COMMs (Optical)

Q-COMMs & Q-Sensing (Microwave)

Q-COMMs (Optical/Microwave)

Q-COMMs (RF/Microwave)

Q-Sensing

Quantum CONOPS Driving technology trades & decisions
What is quantum, and what is it good for?

<table>
<thead>
<tr>
<th>Quantum is:</th>
<th>Quantum enables:</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Particles &amp; Waves (Duality)</td>
<td>• New type of bit – Quantum bit (Qbit)</td>
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<tr>
<td>• Heisenberg Uncertainty</td>
<td>– 2 level system with an infinite alphabet</td>
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<tr>
<td>• Probabilistic Measurement Theory</td>
<td>• Quantum Networking (Teleportation)</td>
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<tr>
<td>• Interference</td>
<td>– Sending 1 Qbit using 2 classical bits &amp; quantum measurements</td>
</tr>
<tr>
<td>• Superposition</td>
<td>• Classical Networking (Super Dense Coding)</td>
</tr>
<tr>
<td>• Coherence</td>
<td>– Sending 2 classical bits using a single Qbit &amp; quantum measurements</td>
</tr>
<tr>
<td>• Tunneling</td>
<td>• Entanglement-enhanced Sensing</td>
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<tr>
<td>• Entanglement &amp; Squeezing (Spooky Action-at-a-Distance)</td>
<td>– Sensitivity, Resolution, timing</td>
</tr>
<tr>
<td></td>
<td>• Physics-based Security</td>
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<tr>
<td></td>
<td>– Eavesdropper detection, random number generation, QKD</td>
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<td></td>
<td>• Computation Speed-up</td>
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<td></td>
<td>– Qbit processor, quantum memory, quantum algorithms</td>
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</table>
Quantum Enabling Technology

**Electron**
- Quantum 1.0

**Photon**
- Quantum 1.5 / 2.0

**Atom**
- Quantum 1.5 / 2.0

- Photon Sources
- Single Photon Detectors
- Entangled Photons
- Squeezed Light
- BEC Chip
- Atom Interferometry (Inertial Sensing)
- Time Reference
- Entangled Photons

- Vacuum Tube
- Transistor
- Integrated Circuit

- • Atom Processor
- • Rydberg RF RX
- • Time Source
- • Gravity Sensor

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## Quantum Enabling Technology

### Electron

**Quantum 1.0**

- **Characteristics**
  - **Mature**
  - Low SWAP
  - Low cost
  - Generally room temperature
  - Broadly applicable
  - Can use Cooper pairs/loops as Qbits; limited scalability
  - Based on macro sensing & measurements
  - Classically limited; exception superconducting devices

### Photon

**Quantum 1.5 / 2.0**

- **Characteristics**
  - Enhanced sensitivity & resolution; below SQL
  - Room temperature (no cryogenic cooling)
  - Capable of enhancing optical, RF/microwave and acoustic systems
  - Highly scalable cluster-state processing
  - **Requires maturation & miniaturization**

### Atom

**Quantum 1.5 / 2.0**

- **Characteristics**
  - Good source of NB entanglement
  - Enhanced sensitivity of RF/microwave signals via Rydberg technology; minimizes need for antennas
  - Enhanced inertial and gravitational sensing via entangled arrays
  - Highly scalable Qbit processing with optical lattices
  - **Requires maturation & miniaturization**
Quantum Technology is Maturing Rapidly

<table>
<thead>
<tr>
<th>PNT</th>
<th>Secure &amp; Covert COMMS &amp; Networking</th>
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</thead>
<tbody>
<tr>
<td>CSAC Physics Pkg.</td>
<td>![Quantum Technology Image]</td>
</tr>
<tr>
<td>Gravimeter</td>
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</table>

### Processing Hardware

<table>
<thead>
<tr>
<th>Hardware</th>
<th></th>
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<tbody>
<tr>
<td>Google - 72 Qbits</td>
<td></td>
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<tr>
<td>IBM - 15 Qbits</td>
<td></td>
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<tr>
<td>Intel - 45 Qbits</td>
<td></td>
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<tr>
<td>Rigetti - 16 Qbits</td>
<td></td>
</tr>
<tr>
<td>IonQ - 32 Qbits</td>
<td></td>
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<tr>
<td>D-Wave - 2000 Qbits</td>
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</tbody>
</table>

### Algorithms

- Quantum Algorithms for Linear Algebra
- Quantum Algorithms for Image Processing
- Quantum Algorithms for Machine Learning

### Cryptography

- RNG
- Key Factory
- QKD Platform

### Covert Sensing - Radar

Equipment from a prototype quantum radar system made by China Electronics Technology Group Corporation Imaginechina via AP Images

Quantum 2.0 is disruptive and here today!
We can Exploit Quantum Advantages

Quantum States
- Superposition
- Entangled
- Squeezed
- Cold

New Algorithms
- Increased Computational Speed
- Enhanced Sensitivity
- Extended Range
- Improved Resolution
- Reduced SWAP-C
- Increased Covertness
- Resilient Communications
- Quantum Networking

Unbreakable Security
- Measure (collapse) the WF
- Detect Eve

Enhanced Inertial Sensing
- Leverage Matter Waves
- Use Entangled Oscillators

Resilient PNT
- Improved Timing

Quantum 2.0 has many practical applications
New Design Patterns (Options)

Information & Channels

Bits → Classical Channel → Bits

Bits → Quantum Channel → Q-Bits → Bits

Q-Bits → Quantum Channel → Q-Bits

Bits → Classical Channel → Bits

Q-Bits → Quantum Channel → Q-Bits

Transmitters & Receivers

Classical TX → Classical RX

Quantum Enhanced TX → Quantum Enhanced RX

Quantum TX → Quantum RX

Quantum 2.0 gives us new design patterns
Top Level Communications Use Cases

**Key Reqs:**
- Covertness
- Security: INFO & TRANS
- Resistant to Interference/Jam
- Data Rates: kbits to Gbits
- Range: m to km
- Channel: Fiber or All Weather Atmosphere

**Arch Considerations:**
- Network Structure
  - Hub/Spoke
  - Mesh
- Network Mobility
  - Static
  - Mobile

Use of Quantum will be driven by requirements
Analyzing Design Options for Communications

Quantum Nets: Quantum entanglement-based routing networks

Classical Secure COMMS: Symmetric & asymmetric (public-key, e.g. RSA) key generation, distribution & mathematics-based encryption … Post Quantum

Quantum Secure COMMS: QRNG, PUFs, QKD & OTP Encryption

Classical P2P COMMS: Classical RF/Microwave/Optical fields-based transmit & receive links

Quantum P2P COMMS: Single & multi-photon (entanglement-based) transmit & receive links

Classical P2P COMMS: Classical RF/Microwave/Optical fields-based transmit & receive links

Quantum Covert COMMS: Low-intensity, single and multi-photon (entanglement-based) communications

Classical Covert COMMS: Spread spectrum & frequency hopping classical communications with RF/Microwave/Optical fields

Quantum is another set of tools/options for design
Top Level Sensing Use Cases

- **Detect & Track Target**
  - **Key Reqs:**
    - All Weather
    - Range/ Angle
    - Rates
    - Sensitivity: high
    - Fast Detect & Track

- **Detect Intrusion**
  - **Key Reqs:**
    - Fiber/Free-Space
    - Range: 100km?
    - Detection time: <s

- **Measure Fields (E/B)**
  - **Key Reqs:**
    - RF, MW or Optical
    - Range: short to long
    - Sensitivity: high
    - Selectivity: high

- **Sense Forces (Inertial/g)**
  - **Key Reqs:**
    - Sensitivity: high
    - Multi-Axes

- **Image (EM/g)**
  - **Key Reqs:**
    - Lab, All Weather
    - Range: short to long
    - Sensitivity: high
    - Resolution: high

Use of Quantum will be driven by requirements
Analyzing Design Options for Sensing

Quantum Target Det. & Imaging: Quantum radar (aka quantum illumination with coherent states, or use of entanglement on local basis to enhance RF/Optical sensing)

Classical PNT: Crystal clocks, gyro technologies (ring laser, fiber optic, tuned rotor, MEM), pendulous accelerometer

Quantum PNT: Atomic clocks, atomic inertial gyroscopes, atomic accelerometers, atomic gravimeters

Classical Sensing: CAT scan, NMR, ground probing, precision machining, manufacturing

Quantum Sensing: Entanglement and quadrature squeezing enhanced interferometry

Quantum Spec. Analysis: Optical and IR entanglement assisted imaging Magnetic and electric field sensing with cold atoms. Entanglement and quadrature squeezing enhanced interferometry

Classical Spec. Analysis: Temperature, RF from DC to daylight, visual and IR imagery, spectral analysis, magnetometers etc.

Remote Sensing
- Physical Devices (Photons, E/B, T, I/V...)
- Target & Image ID ...
- Tomography ...

Industrial Sensing
- Classical
- Quantum

Self Sensing
- Classical
- Quantum

Environ. Sensing
- Classical
- Quantum

Spectrum Analysis ...
- Quantum
- Classical

Classical Target Det. & Imaging: Radar, Lidar, Sonar

Quantum is another set of tools/options

General Dynamics Mission Systems
Validating Designs & Identifying Gaps in Quantum Tech

Key Enabling Tech Gaps
- All weather capable devices
- Environment tolerant devices
- Single, On-Demand Photon Sources
- Discrete & Continuous (Squeezed) Entanglement Sources
- Single Photon Detectors
- Transducers
- Optimal Receivers
- Memory
- Repeaters, Switches & Routers
- Source & Channel Coding
- Architectures
- Direct/Feedback
- Distributed

Trades necessary to validate use of quantum, and gaps in tech
Peering into the Future of Communications & Sensing

• Systems Perspective
  – Think of entanglement as a network resource
  – A network that continually generates, distributes, stores and consumes entanglement

• Many Uses
  – General purpose quantum computing
  – Distributed quantum computing
  – Entanglement assisted sensing
  – Entanglement assisted communications
  – Entanglement assisted security

Quantum networks will be built using entangled photons & squeezed light
What are we doing to make a difference?

- **Collaborative quantum R&D:**
  - Secure communications
  - Covert communications (LPI/LPD)
  - Long-range communications
  - Remote sensing & imaging
  - Optimization

- **Approach:**
  - Sponsoring R&D with leading research universities to build relations, leverage research and advance technology transition
  - Collaborating with US government laboratories, agencies to prototype, demonstrate and transition new technology
  - Researching, developing and demonstrating prototype capabilities

Exploring quantum advantages to provide enhanced capabilities
Entanglement-Enhanced Secure Communications

Using Entanglement to Enhance Secure Communications in High Noise Environments

35 dB Quantum Advantage in High Noise

Objectives
- Co-existing quantum/classical channels
- Entanglement-enhanced decoding
- Quantum vs classical receiver architecture

\[ \log_{10}(\text{BER}) \]

60 dB disparity

References:
10.1103/PhysRevLett.111.010501, 10.1103/PhysRevLett.114.110506
Entanglement-Enhanced RF Sensing

Using Squeezed Vacuum to Improve RF Sensing

Using Squeezed Light to Enhance RF Sensing
Quantum is in our Future

• We believe quantum will foster the next great leap in technology & industry
• We are investing in quantum technology
• We are expanding our own quantum laboratory
• We are developing a quantum workforce
• We are developing prototype quantum COMMS & sensing systems

• If you are interested in learning more, please visit us at
Thank you!