Multi-channel Communication in Free-Space Optical Networks for the Last-mile

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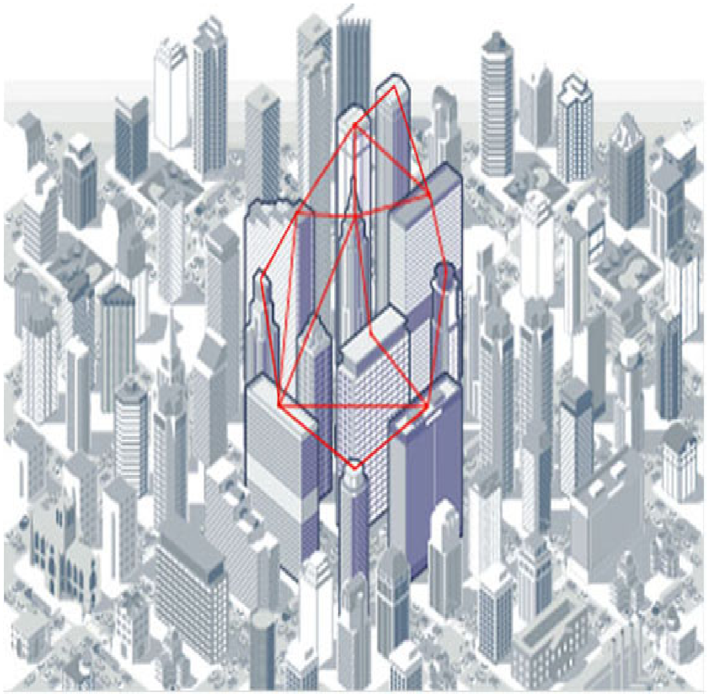
Outline

1. Motivation
2. A Brief Introduction to Free-Space Optical Networks
3. Multi-element Optical Antennas for Broadband Access
4. Inter-Channel Interference and Array Capacity
5. Array Designs
6. Design Guidelines

Motivation

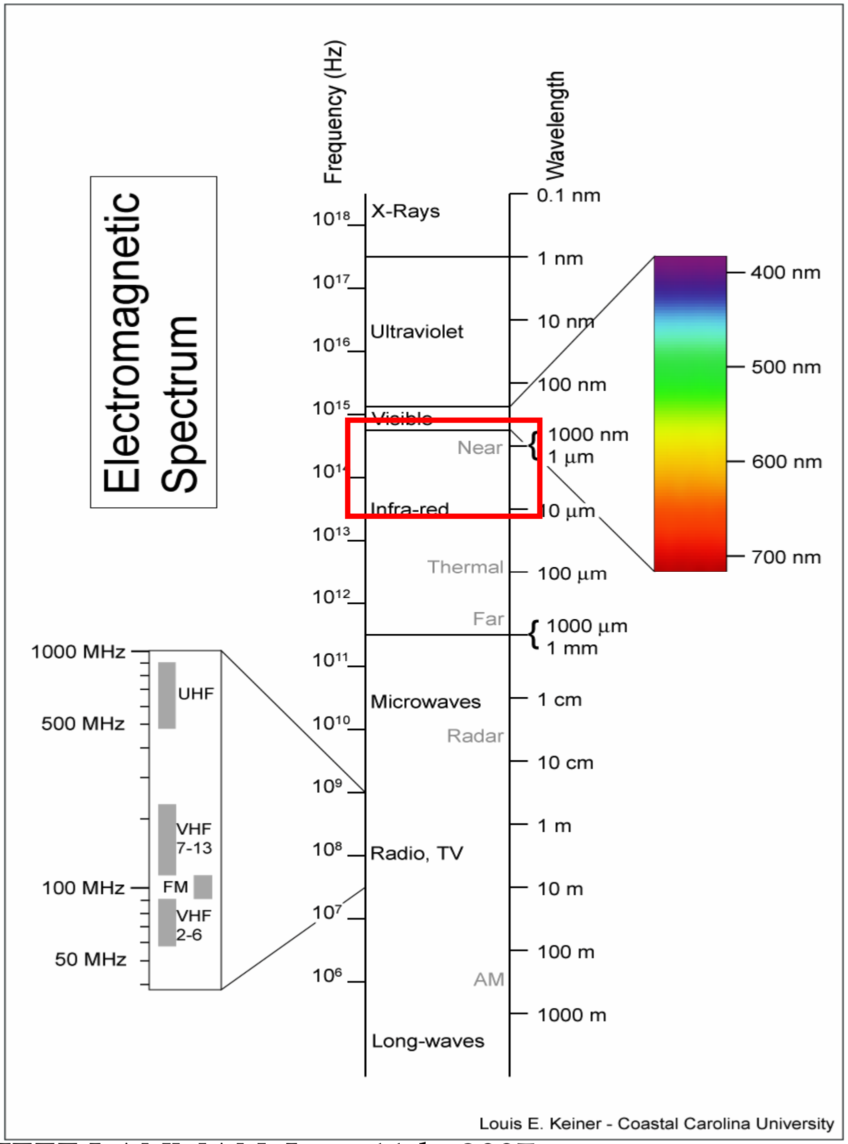
- Tremendous need for a broadband wireless access technology that can support the high bandwidth requirements
  - Ex. Wireless Mesh Networks (WMNs)
  - Wireless backbone for metro/urban area networks.
  - Opportunistic networks

- Free-Space optical networks can **complement** RF-based WLAN technologies like 802.11b/a, and WMAN technologies like 802.16.
- Data transfer through atmosphere using modulated light pulses.
- Currently serves point-to-point links between buildings in a metro area



From LightPointe Optical Wireless Inc.

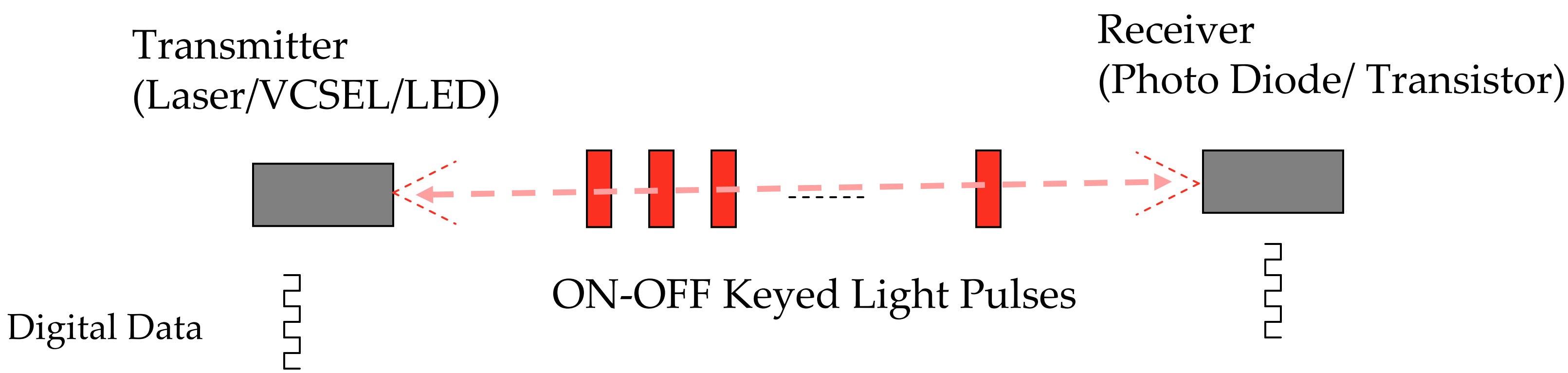
Free Space Optical Communications



- FSO **pros**:
  - very **high bandwidth**: Gbps to Tbps
  - very **limited interference**, i.e. spatial re-use
    - Nodes can be equipped with multi-element directional antennas for higher capacity.
  - lower power consumption
  - license-free operation
  - low-cost options are available e.g., VCSELs and HBLEDs
  - quick and easy installation (in comparison to fiber)

- FSO **cons**:
  - **Line of sight** (LOS) requirement
  - LOS **alignment**, i.e. very sensitive to vibrations and sways

Typical FSO Communication System

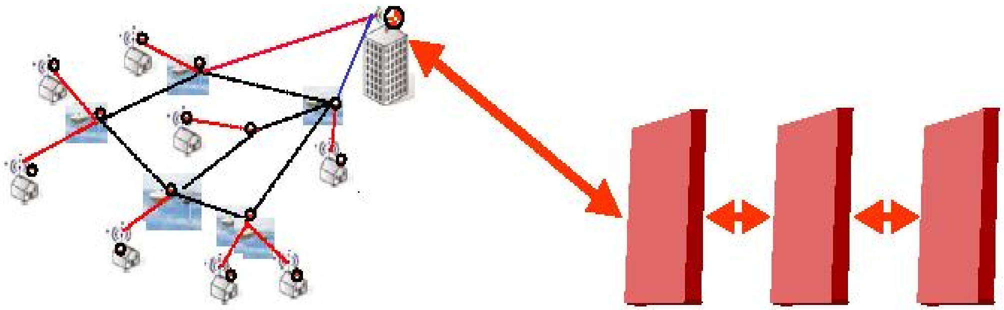


Challenges:

- Light beam is directional:
  - needs line-of-sight alignment between the transceivers for communication.
- Single link is more susceptible to blockage or loss of connectivity:
  - needs spatial redundancy

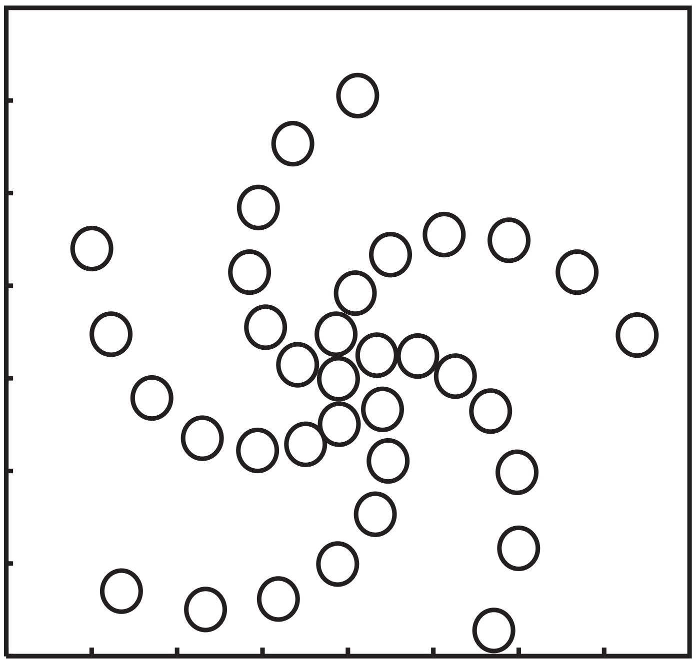
FSO Arrays: High Aggregate Bandwidths

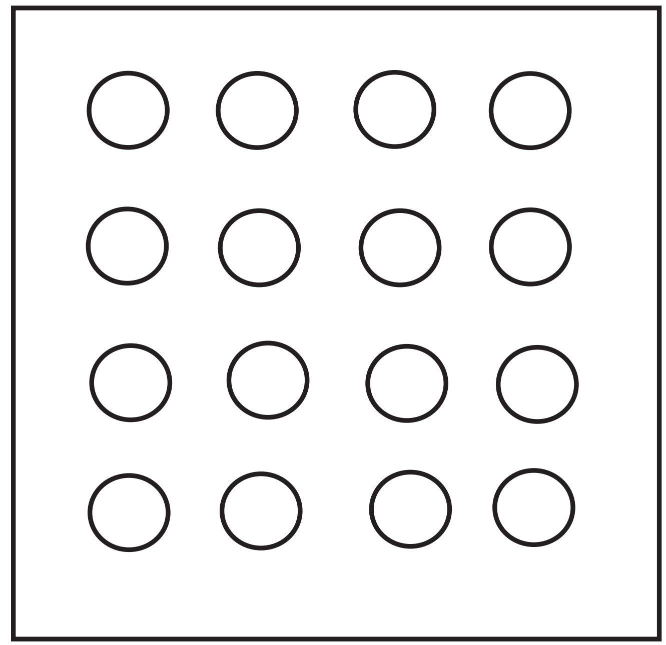
- By closely packing the FSO transceivers, can we achieve very high aggregate bandwidth (> 100Gbps)?
  - If so, FSO arrays are suitable for broadband access and backhaul applications
- We analyze the error due to inter-channel interference and model the channel capacity between FSO arrays.
- We provide design guidelines on the choice of parameters for FSO arrays using our analysis and simulations.



E.g.: Hybrid/FSO network with 2-D arrays and spherical arrays

Array Designs : Helical vs. Uniform Transceiver Placement





Helical array design gives more capacity for a given range and transceiver parameters due to reduced inter-channel interference.

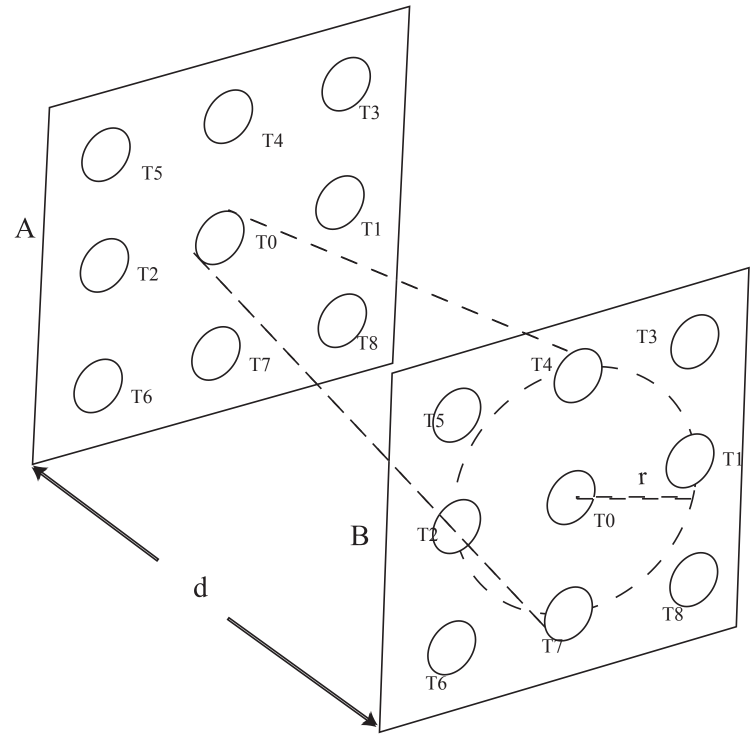
2-D FSO Arrays

- 2 Dimensional array parameters:
  - d: distance between arrays
  - θ: divergence angle of a transceiver
  - ρ: Package density of the transceivers
  - C: Capacity between arrays

- There can be several geometrical patterns for the transceiver layouts on the 2-D array.

- We obtain a general expression for the error probability due to interference.

- The geometry of arrays decides the capacity 'C' between the arrays .
  - We look at two such designs.



$$r = d \tan \theta$$

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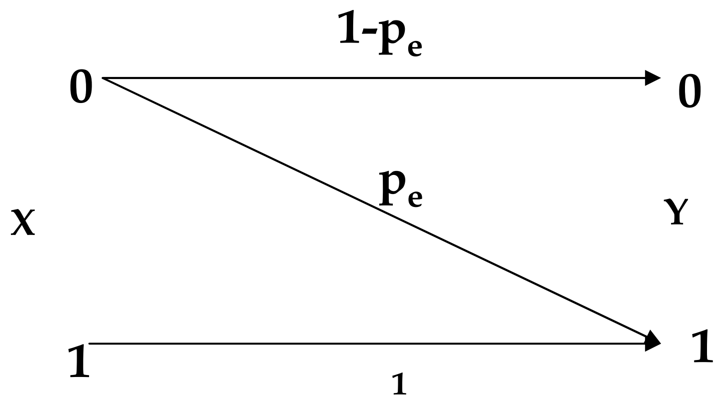
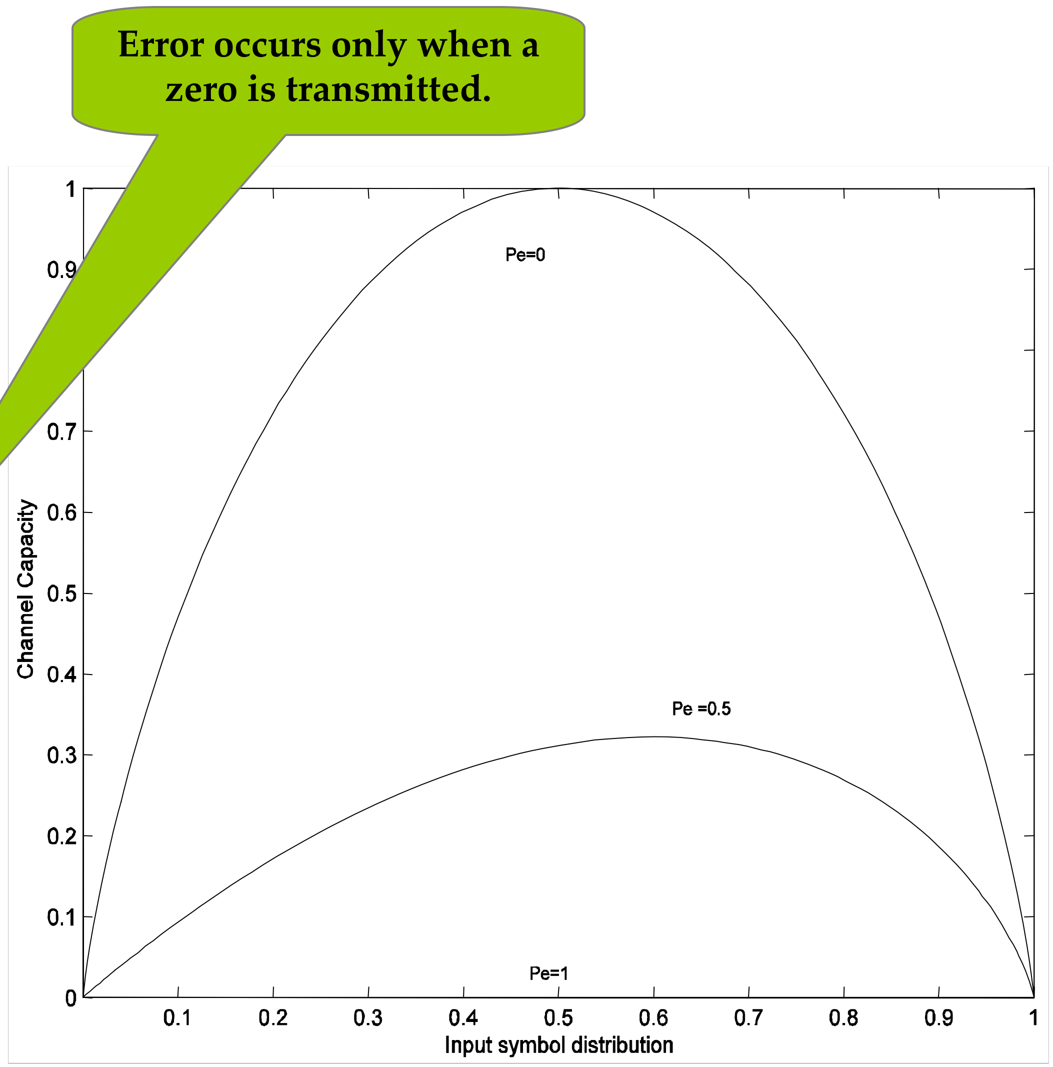
Capacity Between Arrays: Binary Asymmetric Channel



- The capacity of such a **BAC** is given by:

$$C = \max_{p(x)} H(\overline{p_0}.\overline{p_e}) - \overline{p_0} H(p_e)$$

- We fix p_0 at 0.5; and find the error probability p_e for various designs.



Error Due to Inter-channel Interference

The received signal $r(t)$ can be represented as:

$$r(t) = s(t) + \eta + \zeta$$

Combine these two into a single Gaussian

where η is the Gaussian noise due to thermal noise and ζ is the inter-channel interference from K undesired users. This can be equivalently written as

$$r(t) = \sum_{k=0}^{K} s_k(t) + n_k(t)$$

Error Due to Inter-channel Interference

Let us combine η and ζ into a single Gaussian random variable ξ. I.e.,

$$\xi = \eta + \zeta$$

Then the error probability for free-space optical communications with on-off keying is defined as:

$$p_e = p(\xi \geq I_T) \cdot p(\text{The desired user transmits a 0})$$

This is because an error occurs only the signals from the undesired transmitter is a "1" and the signal from the desired transmitter is "0".

Error Due To Inter-channel Interference

- The general expression for error probability due to inter-channel interference for a multi-element antenna:

- The **number of interferers K** for a given set of parameters decides the error probability. The geometry of the array in turn decides the number of interferers.

$$P_e = Q\left(\frac{I_T}{2\sqrt{\frac{1}{2}\sum_{k=0}^{K-1} e^{-\left(\frac{\theta_k}{\theta}\right)^2} + \frac{N_0 T_b}{4}}} \right)$$

Variance of interference

Variance of thermal noise

where θ is the divergence angle of the source, θ_k is the angle at which the k^{th} interferer is transmitting, N_0 is the PSD of the Gaussian noise, T_b is the bit period and I_T is the threshold intensity for a logic 1.

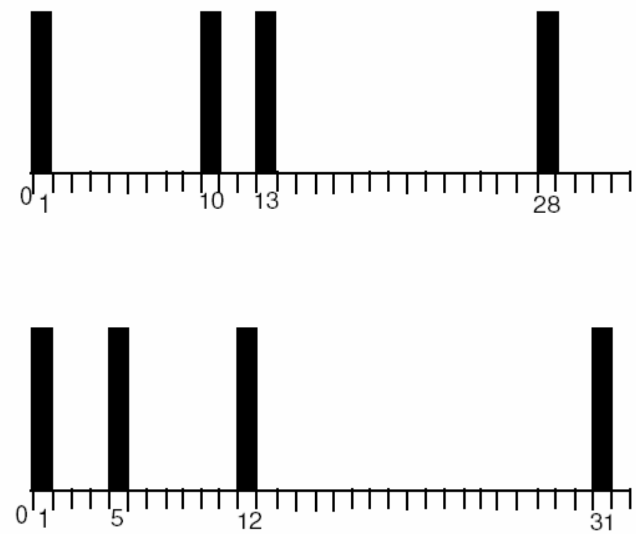
Struggling with Inter-channel Interference

- Hardware based: Using multi-wavelength transmitters and receivers; spatially separate the same wavelength transmitters

- Orthogonal Codes: Optical Orthogonal Codes (OOCs) can be used to identify individual transmitters.
  - OOCs were originally developed for optical fiber communications. [Salehi89]

Optical Orthogonal Codes

- Optical signals form a positive system; therefore, the cross correlation coefficient and auto-correlation coefficients are taken to be 1.
- The receiver is a energy detector; by setting the threshold appropriately, a '**0**' or '**1**' is detected.



Two OOCs with weight N=4 and length F=32. Each transceiver uses a unique code similar to CDMA wireless users in a cell.

Error Probability Due To Inter-channel Interference In The Arrays When OOCs Are Used.

$$p_e = Q(\frac{I_T}{2\sigma_\xi})$$

where

$$\xi = \eta + \zeta_{ooc}$$

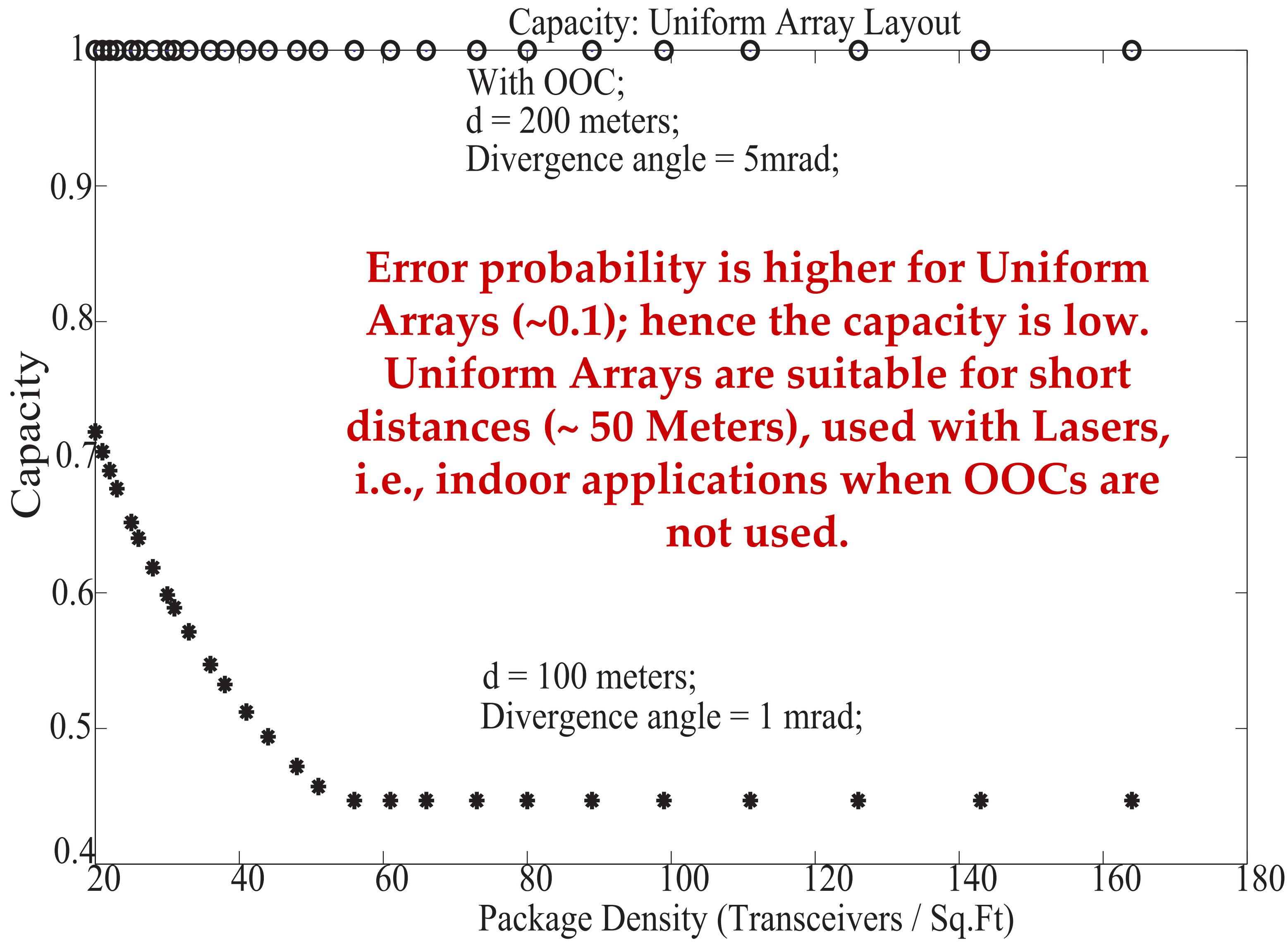
Combined Interchannel Interference with OOCs and Guassian Noise

The probability of error after using optical orthogonal codes is then given by:

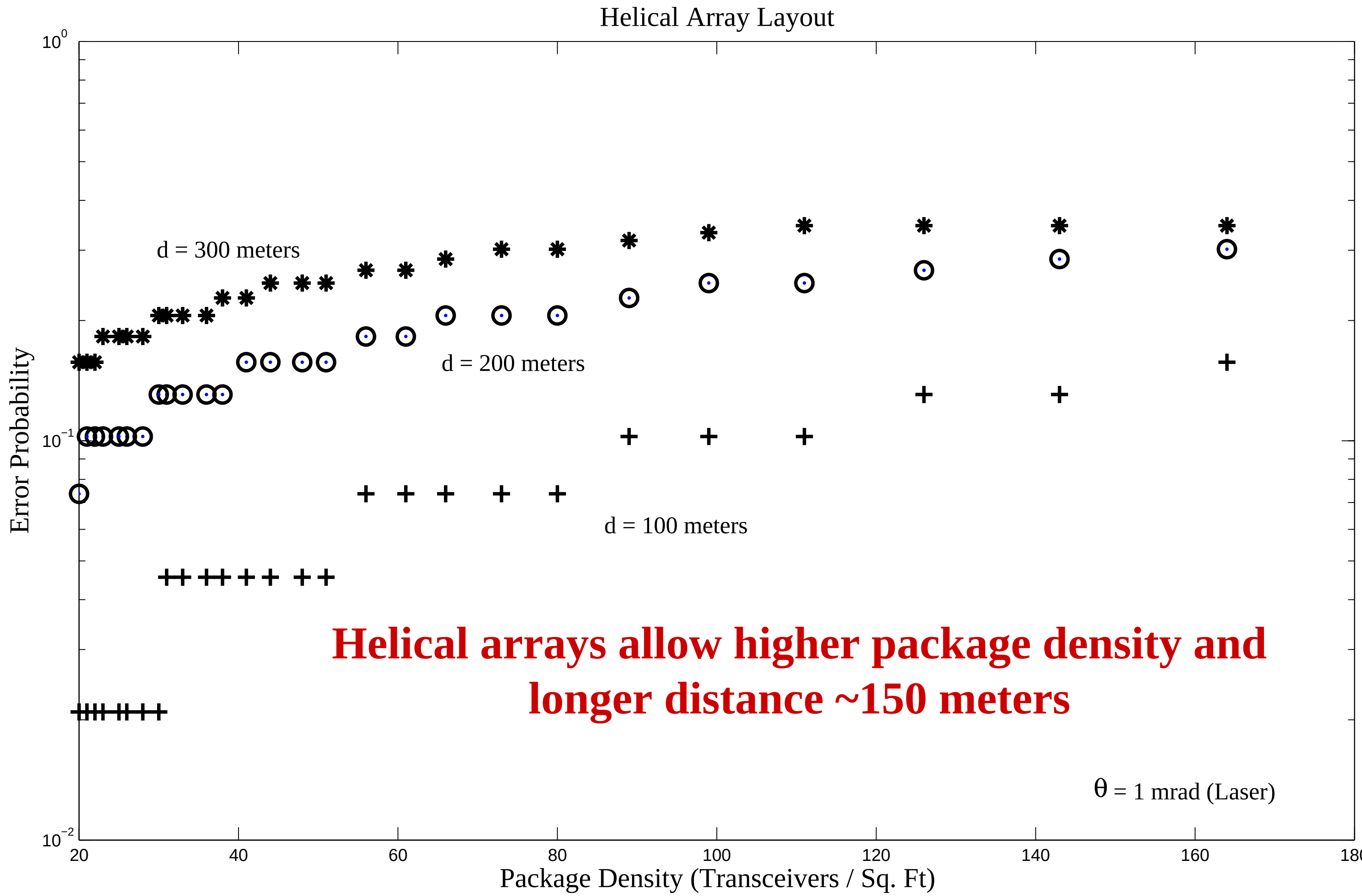
$$p_e = Q(\frac{I_T}{2\sqrt{(\frac{N^2}{2F})(1-\frac{N^2}{2F})\sum_{k=0}^{K-1} e^{-(\frac{4\theta_k}{\theta})^2} + \frac{N_0 T_b}{4}}}) \quad (4.2)$$

Factor reducing the error.

Per-Channel Capacity of The Uniform Arrays

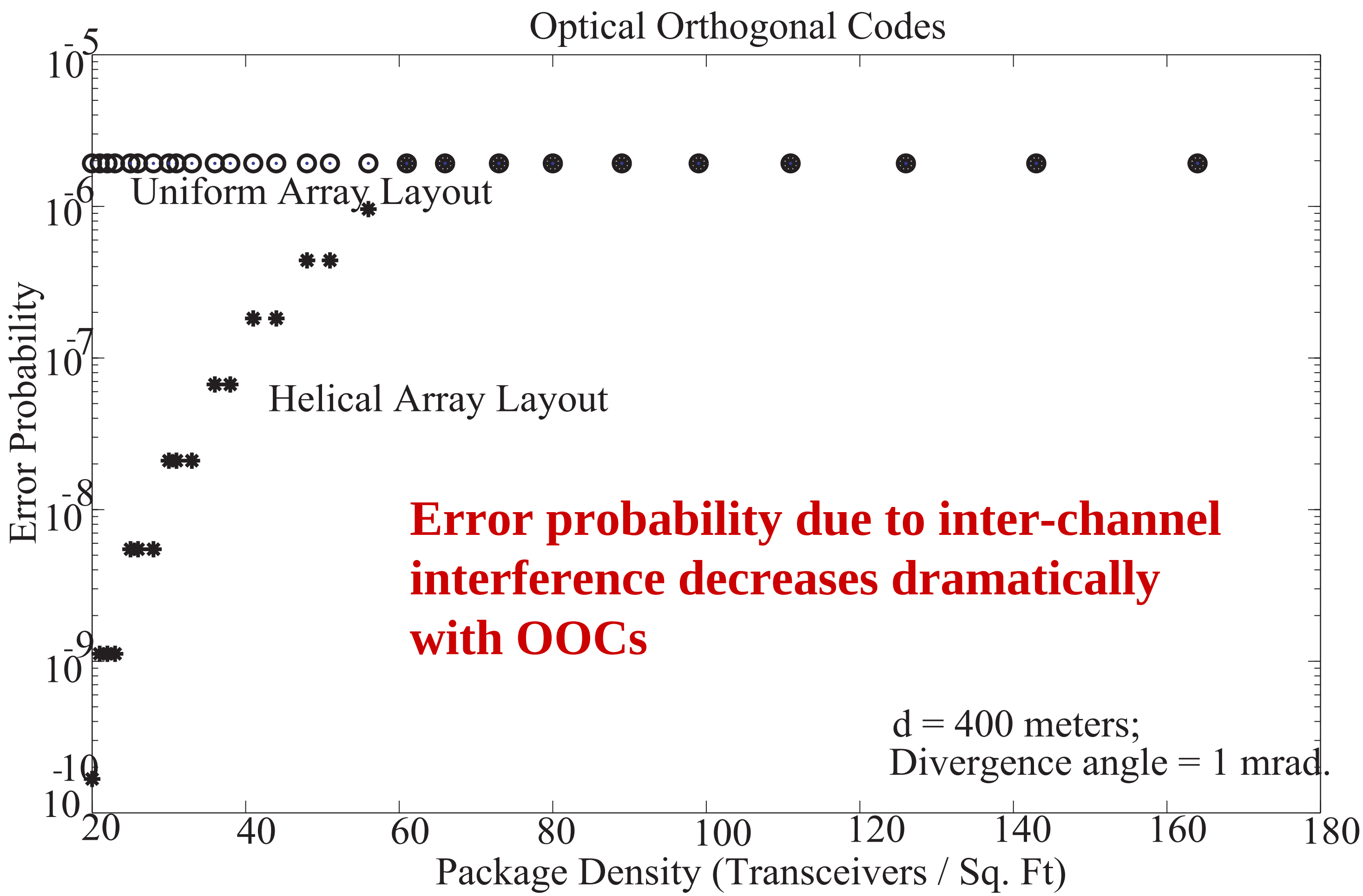


Error Probability For The Helical Arrays

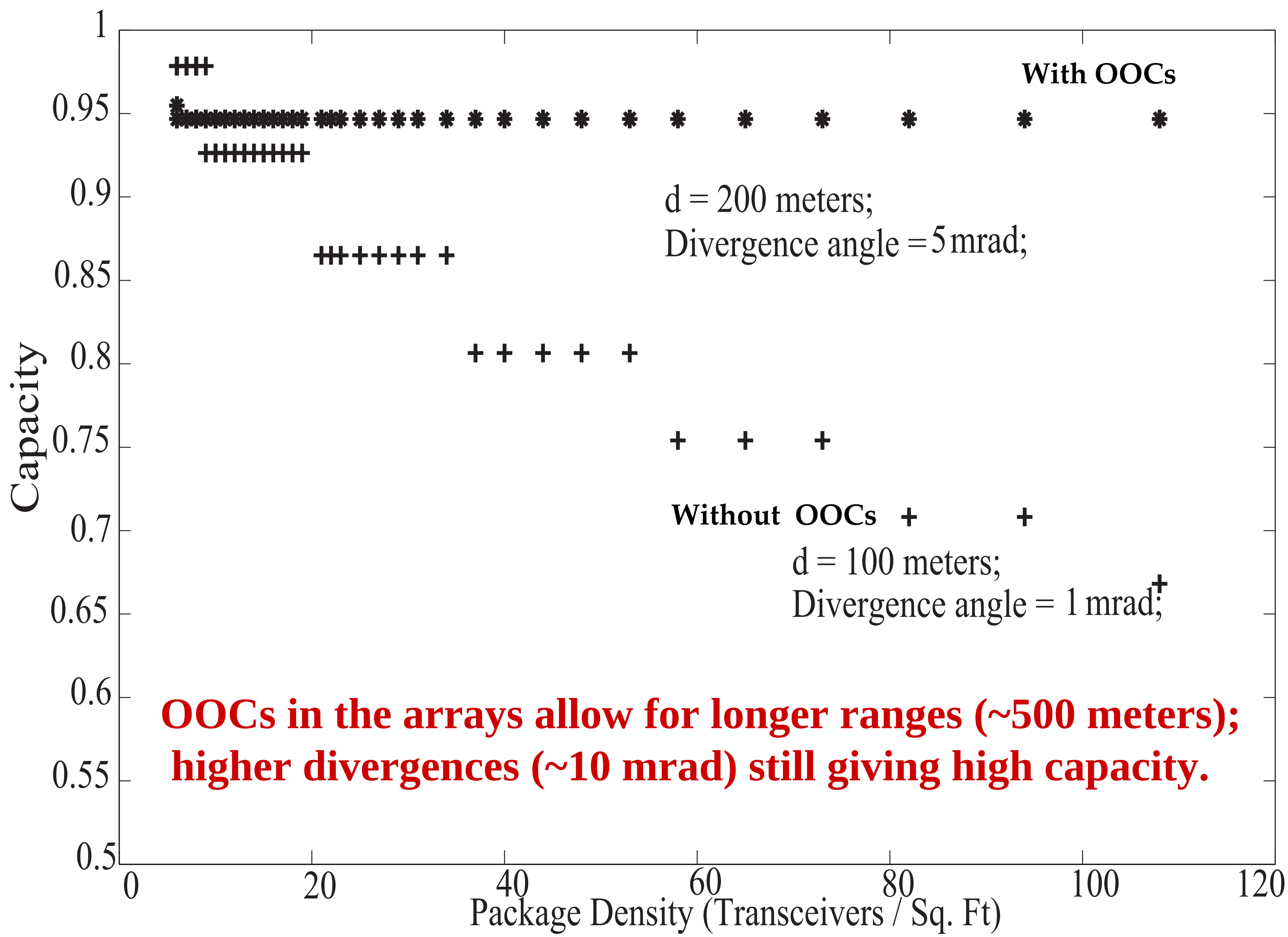


Helical arrays allow higher package density and longer distance ~150 meters

Error Probability Due To Inter-channel Interference In The Arrays When Oocs Are Used.

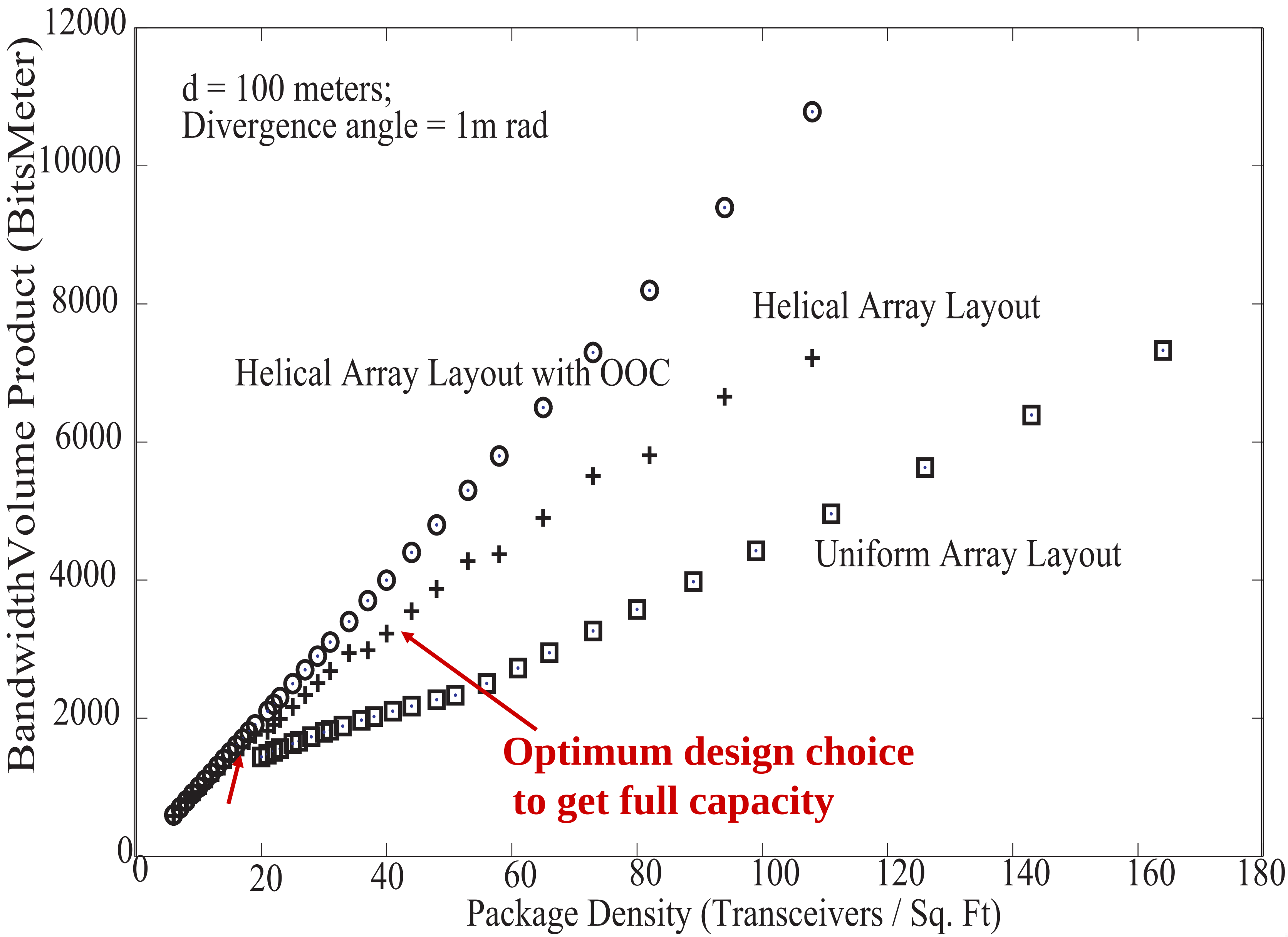


Helical Array Capacity



OOCs in the arrays allow for longer ranges (~500 meters); higher divergences (~10 mrad) still giving high capacity.

Bandwidth-Volume Product



Contributions

- Channel capacity between arrays is interference limited. We derived general expressions for error probability for the arrays with and without orthogonal codes.
- Smaller the beam divergence, better is the capacity for a given range. This also means higher bandwidth.
- Non-uniform placement of transceivers allow for higher package densities of transceivers.
- With the use of OOCs we can achieve near ideal capacities for the arrays; The bandwidth for such arrays is limited only by the number of OOCs that can be implemented.
- Example:
  - An array with 5 channels at full capacity, each operating at 100 Mbps, with an aggregate bandwidth of 0.5 Gbps.
  - Alternatively, we can pack 10 channels, each operating at 3/4^{ths} of its capacity and with an aggregate bandwidth of 0.75 Gbps.
- We introduce a **metric** that measures effectiveness of 2-D array FSO communication: "Bandwidth-Volume Product".

Future Work

- Spatial codes on 2-D arrays to improve FSO link reliability.
- Optimization of the location of the transceivers on the array to maximize the bandwidth.
- Analysis of multiple hops using array antennas to achieve both spatial redundancy and robustness against atmospheric adversities.

Thank you