Scalability of the Channel Capacity of Electromagnetic Nanonetworks

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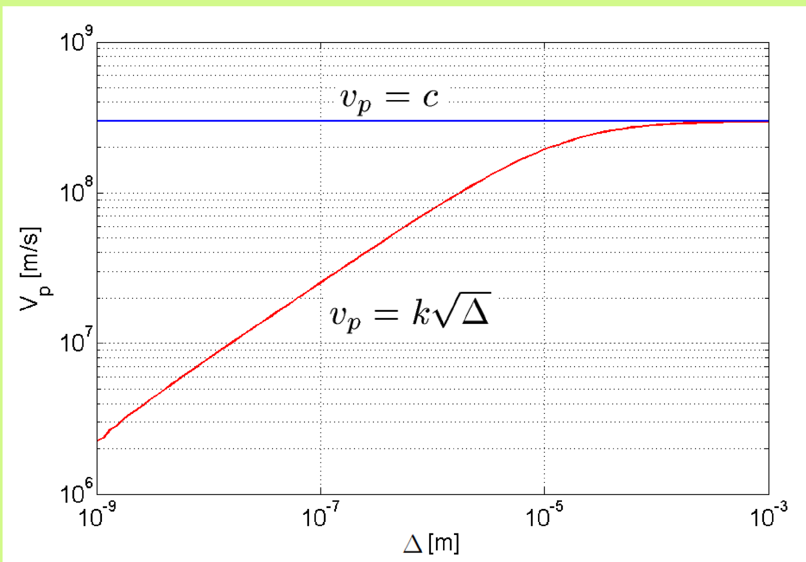
Network scalability

- How does the channel capacity scale when the network dimensions shrink into the nanoscale?
- We consider the scalability of the capacity of a point-to-point link, where both transmitter and receiver are in the nanoscale
- The scale parameters are:
  - Δ: nanodevice size
  - d: transmission distance
- We want to study the scalability when $\Delta\rightarrow 0$, $d\rightarrow 0$

Quantum effects

- When using CNT/GNR-based antennae to radiate electromagnetic waves in the nanoscale, there appear quantum effects due to the ballistic transport of electrons in graphene:
  - Macro-scale behavior: $v_p = c$
  - Quantum behavior: $v_p = k\sqrt{\Delta}$



- We study whether these effects actually benefit or harm communication

Nano-EM channel capacity

- The capacity of a frequency-selective communication channel can be obtained using the Shannon-Hartley theorem:

$$C = \max_{S(f): \int S(f)df \le S_T} \int_0^B \log_2\left(1 + \frac{S(f)}{A(f)N_0}\right) df$$

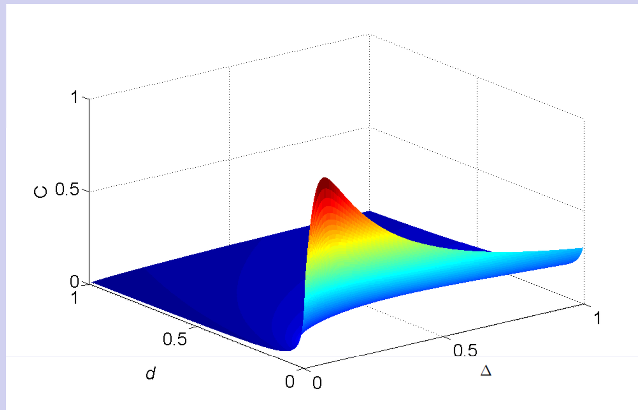
- We assume the following expressions for the radiated power spectral density and the channel attenuation:
  - Spectrally-flat radiated power $S(f) = \frac{S_T}{B}$
  - Free-space propagation loss $A(f) = \left(\frac{4\pi d f}{c}\right)^2$

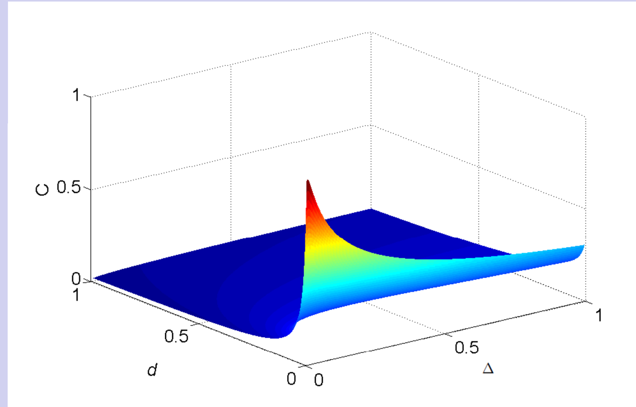
Scalability of channel capacity

- The channel capacity scales differently whether we consider or not the quantum phenomena:

$$C_{nq} = \Theta\left(\frac{1}{\Delta}\log\left(1+\frac{\Delta^3}{d^2}\right) + \frac{\sqrt{\Delta}}{d}\arctan\left(\frac{d}{\Delta^{3/2}}\right)\right)$$

$$C_q = \Theta\left(\frac{1}{\sqrt{\Delta}}\log\left(1+\frac{\Delta^{3/2}}{d^2}\right) + \frac{\sqrt[4]{\Delta}}{d}\arctan\left(\frac{d}{\Delta^{3/4}}\right)\right)$$



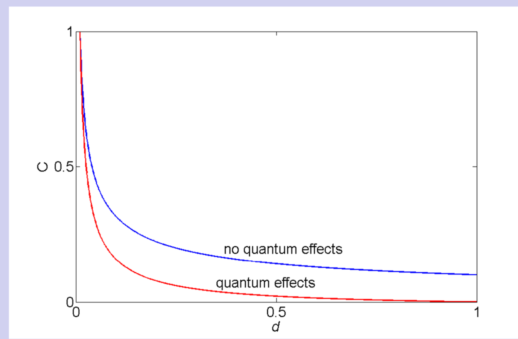


Capacity limits in the nanoscale

- The expressions above do not have a unique limit when $\Delta\rightarrow 0$, $d\rightarrow 0$
- In order to find the limit expressions, we need to do an assumption on the relationship between Δ and d. There are 3 interesting cases:
  - When $\Delta = \Theta(d)$, in the limit $d\rightarrow 0$ the capacity increases at a higher rate when considering the quantum effects:

$$C_{nq} = \Theta\left(\frac{1}{\sqrt{d}}\right)$$

$$C_q = \Theta\left(\frac{-\log d}{\sqrt{d}}\right)$$



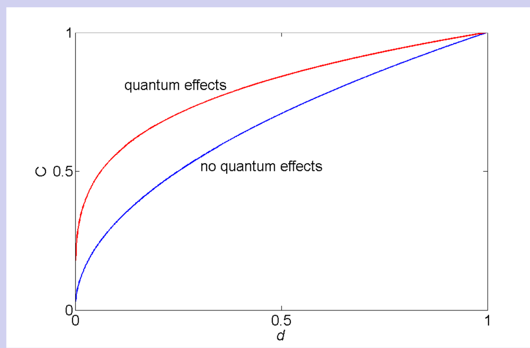
  - When $\Delta = \Theta(1)$, the capacity increases at the same rate whether we include quantum effects or not:

$$C_{nq} = \Theta(-\log d) \qquad C_q = \Theta(-\log d)$$

  - When $d = \Theta(1)$, the capacity decreases at a higher rate when we include quantum phenomena:

$$C_{nq} = \Theta\left(\sqrt{\Delta}\right)$$

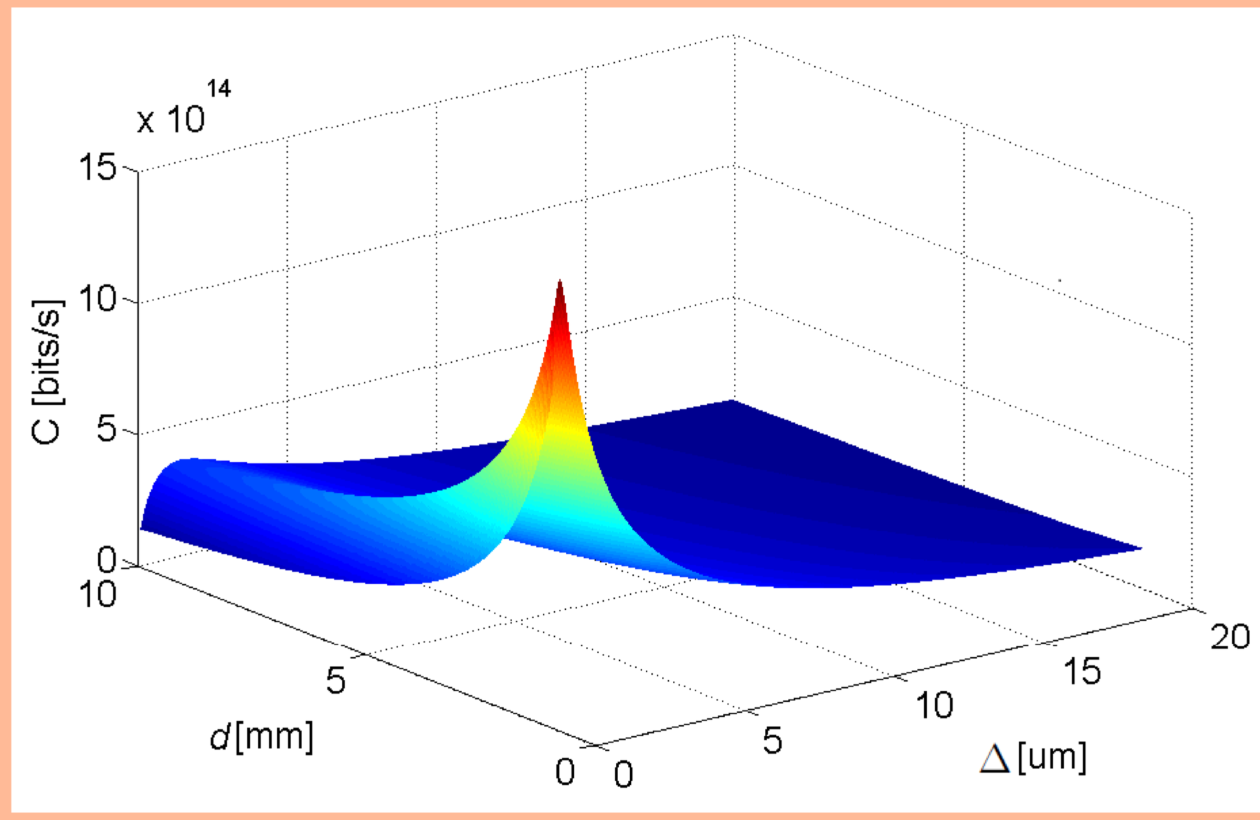
$$C_q = \Theta\left(\sqrt[4]{\Delta}\right)$$



Numerical results

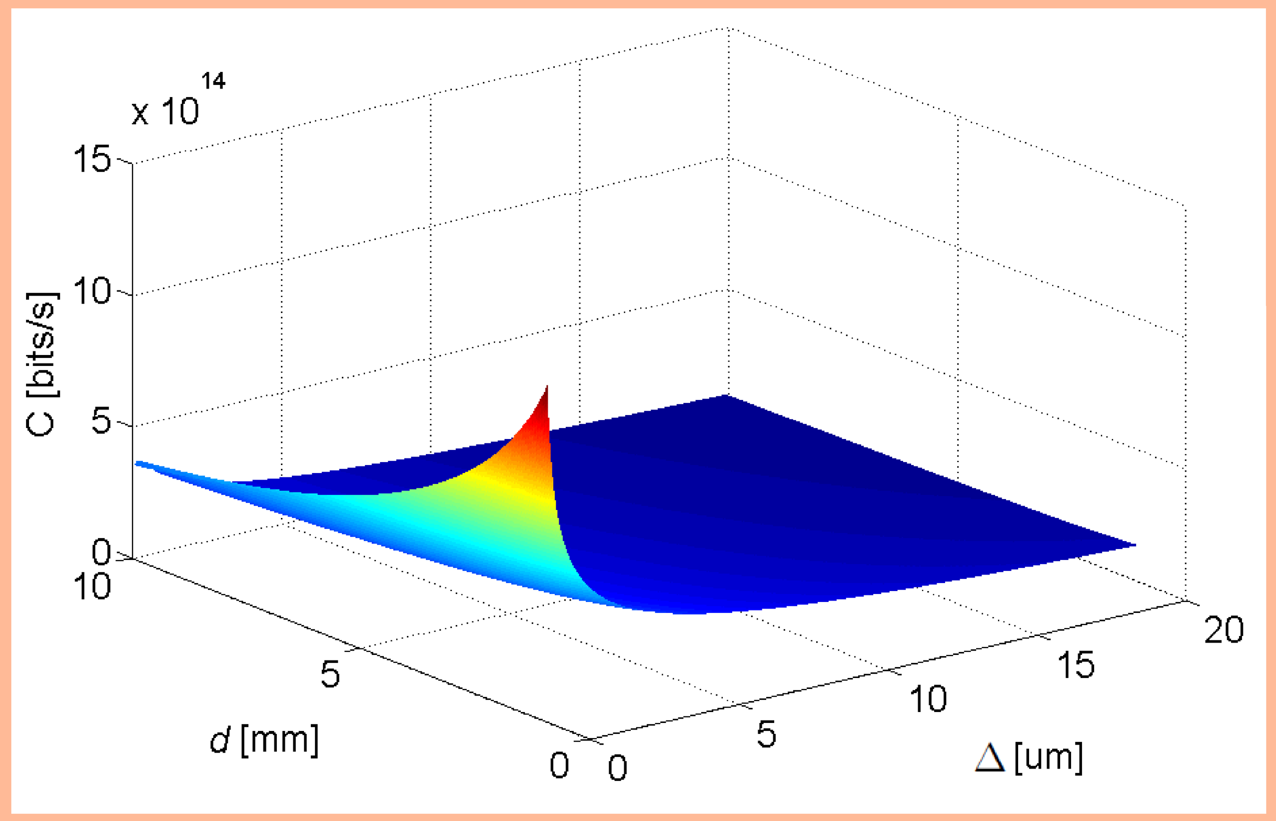
- In order to obtain quantitative results of the channel capacity, we give realistic values to the parameters of the capacity expression:
  - Δ from 100 nm to 20 μm
  - d from 1 to 10 mm

Without quantum effects



- Without quantum effects:
  - High channel capacity
  - Capacity tends to 0 when $\Delta\rightarrow 0$
  - ➢ There is an optimal antenna size

With quantum effects



- With quantum effects:
  - Lower channel capacity
  - Capacity tends to ∞ when $\Delta\rightarrow 0$: there is no peak in capacity
  - ➢ The smaller the antenna, the better!

Second Nanonetworking Day - June 23rd, 2010