Exploring the Scalability Limits of Communication Networks at the Nanoscale

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Nanonetworks
Nanotechnology is envisaged to allow the development of nanometer-scale machines

- **Nano-EM**
- **Biological**

Nanotechnology is envisaged to allow the development of nanometer-scale machines

- Nano-EM
- Biological

The capabilities of nanomachines are **constrained** by their limited detection/actuation range.

**Nanonetworking** is an emerging field studying communication among nanomachines.

The resulting nanonetworks will greatly **expand** the capabilities of a single nanomachine.
Current network protocols and techniques cannot be directly applied to communicate nanomachines.

Two main paradigms emerge:

- **Nano-electromagnetic** communication
- **Molecular** communication
Graphene-based nano-antennas (CNTs and GNRs) are envisaged to implement nano-EM communications. Due to the lower wave propagation speed in graphene, graphene-based nano-antennas radiate EM waves in the THz band.

Information is encoded inside **molecules**

- **Ca**\(^{2+}\)
- **DNA**
Molecules are sent among nanomachines

- Brownian motion
- Spontaneous diffusion

Applications of nanonetworks

- Wireless NanoSensor Networks (WNSN)
- Intrabody disease detection and cooperative drug delivery systems

Motivation of this thesis

How different will nanonetworks be from traditional electromagnetic networks?

We need a scalability theory for nanonetworks

- Study the performance metrics of the network
  - Throughput
  - Transmission delay
  - Energy consumption
  - ...

- When the network size is reduced to the nanoscale
Main contributions

- Scalability analysis of the **channel capacity** of electromagnetic nanonetworks

- **Characterization** (both analytically and by simulation) of the physical channel of diffusion-based molecular nanonetworks

- Scalability analysis of several **performance metrics** using a pulse-based modulation in the previous scenario
Scalability of the channel capacity of electromagnetic nanonetworks
Scalability of the channel capacity of EM nanonetworks

- Bandwidth $\sim$ THz $\rightarrow$ very high channel capacity

- Quantum effects in the nano-EM physical channel
  - Lower wave propagation speed
    \[ v_p = \frac{1}{\sqrt{LC}} \]
  - Molecular absorption
    \[ A_{\text{abs}} = \frac{1}{\tau} = e^{kd} \]
  - Molecular noise
    \[ T_{\text{mol}} = T_0 (1 - \tau) = T_0 \left(1 - e^{-kd}\right) \]
    Only appears when signal is transmitted
How do these quantum effects affect the channel capacity at the nanoscale?

We particularize Shannon’s law for the frequency-selective nano-EM channel

\[
C = \max_{S(f): \int_B S(f) df \leq P_T} \int_B \log_2 \left( 1 + \frac{S(f)}{A(f)N(f)} \right) df
\]
We obtain analytical expressions of the channel capacity as a function of $\Delta$, $d$ and $P_T$

\[
C_{nq} = \frac{c}{2 \log(2)\Delta} \log \left( 1 + \frac{\Delta^3 P_T/d^2}{2 \pi^2 c N_0} \right)
+ \frac{\sqrt{c \Delta P_T/d^2}}{\log(2) \pi \sqrt{2 N_0}} \arctan \frac{\pi \sqrt{2 c N_0}}{\sqrt{\Delta^3 P_T/d^2}}
\]

\[
C_q = \frac{k_1}{2 \log(2) \sqrt{\Delta}} \log \left( 1 + \frac{c^2 \Delta^{3/2} P_T/d^2}{2 \pi^2 N_0 k_1^3} \right)
+ \frac{c^4 \Delta \sqrt{P_T/d^2}}{\log(2) \pi \sqrt{2 N_0 k_1^3}} \arctan \frac{\pi \sqrt{2 N_0 k_1^3}}{\sqrt{P_T/d^2} c \Delta^{3/4}}
\]

$\Delta$: nanomachine length  
$d$: transmission distance  
$P_T$: transmitted power  
$N_0$: noise power spectral density  
$c$: speed of light  
k_1$: constant
We find the limits of the previous expressions when $\Delta \to 0$, $d \to 0$ and $P_T \to 0$

We derive the necessary conditions to keep the network feasible

- The transmission distance needs to scale proportionally to the nanomachine length: $d = \Theta(\Delta)$
- The scalability of the transmitted power $P_T$ depends on whether quantum effects are present
Scalability of the transmitted power $P_T$ as a function of the nanomachine size $\Delta$.

\[ P_{T_{\text{noq}}} = \Omega(\Delta) \]

\[ P_{T_{\text{q}}} = \Omega(\Delta^{3/2}) \]

With quantum effects
Without quantum effects
Diffusion-based channel characterization in molecular nanonetworks
**Diffusion-based channel characterization**

- Transmitters encode information into the release pattern of molecules
- Emitted molecules move according to Brownian motion
  - Fick’s laws of diffusion
- Receivers measure the local concentration of molecules and decode the information

The diffusion-based molecular channel is very different from the traditional EM channel

- Bandwidth $\sim$ kHz $\rightarrow$ low channel capacity
- Long propagation delay
- Very energy efficient
- New sources of noise
  - Brownian motion
  - Molecules are discrete

We need to characterize this channel in order to study the scalability of diffusion-based molecular communication
We propose a pulse-based modulation scheme

\[ c(r, t) = \frac{Q}{(4\pi D t)^{3/2}} e^{-r^2/4Dt} \]

- \( Q \): number of emitted molecules
- \( D \): diffusion coefficient
- \( r \): transmission distance
- \( t \): time
We find analytical expressions for the most relevant metrics from the communication standpoint.

- **Pulse delay**
  
  \[ t_d = \frac{r^2}{6D} \]

- **Pulse amplitude**
  
  \[ c_{max} = \left( \frac{3}{2\pi e} \right)^{3/2} \frac{Q}{r^3} \]

- **Pulse width**
  
  \[ t_w = \frac{0.4501}{D} r^2 \]

*Q*: number of emitted molecules  
*D*: diffusion coefficient  
*r*: transmission distance
Diffusion-based channel characterization

The results are validated by simulation

Pulse delay

Pulse amplitude
Diffusion-based channel characterization

Pulse width

Transmission distance [nm] vs. Pulse width [ns]

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Scalability of the performance metrics of the diffusion-based molecular channel compared to the wireless EM channel

<table>
<thead>
<tr>
<th>Metric</th>
<th>EM channel</th>
<th>Molecular channel</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pulse delay</td>
<td>$\Theta (r)$</td>
<td>$\Theta (r^2)$</td>
</tr>
<tr>
<td>Pulse amplitude</td>
<td>$\Theta (1/r^2)$</td>
<td>$\Theta (1/r^3)$</td>
</tr>
<tr>
<td>Pulse width</td>
<td>$\Theta (1)$</td>
<td>$\Theta (r^2)$</td>
</tr>
</tbody>
</table>
Conclusions and outcomes
Nanonetworks will greatly expand the range of applications of nanotechnology.

We lay the foundations of a scalability theory for nanonetworks:

- The use of graphene-based antennas gives electromagnetic nanonetworks a scalability advantage over traditional networks.
- The studied metrics in molecular nanonetworks scale worse than in wireless electromagnetic networks.
Research outcomes

4 papers


2 co-supervised master thesis


Iñaki Pascual, “NanoSim: Simulation Tool for Diffusion-based Molecular Communication in Nanonetworks”.

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