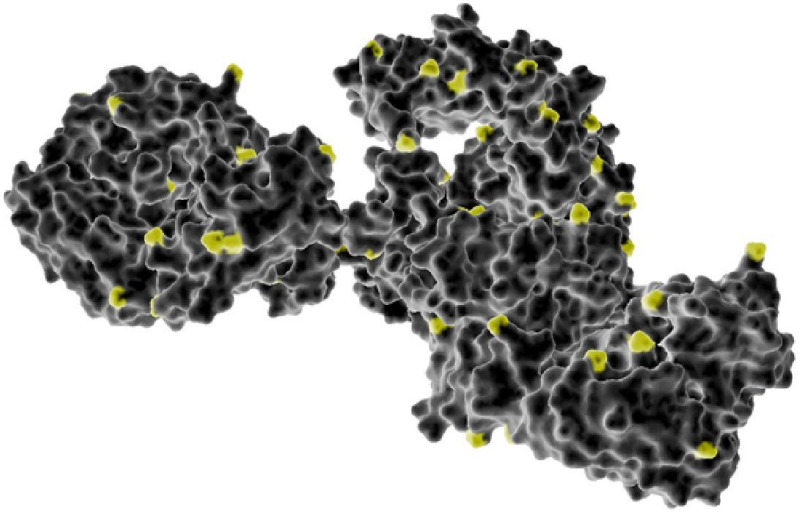
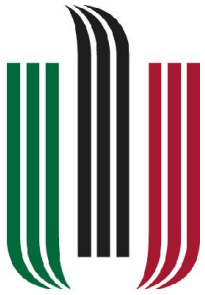


# Nanoscale communications

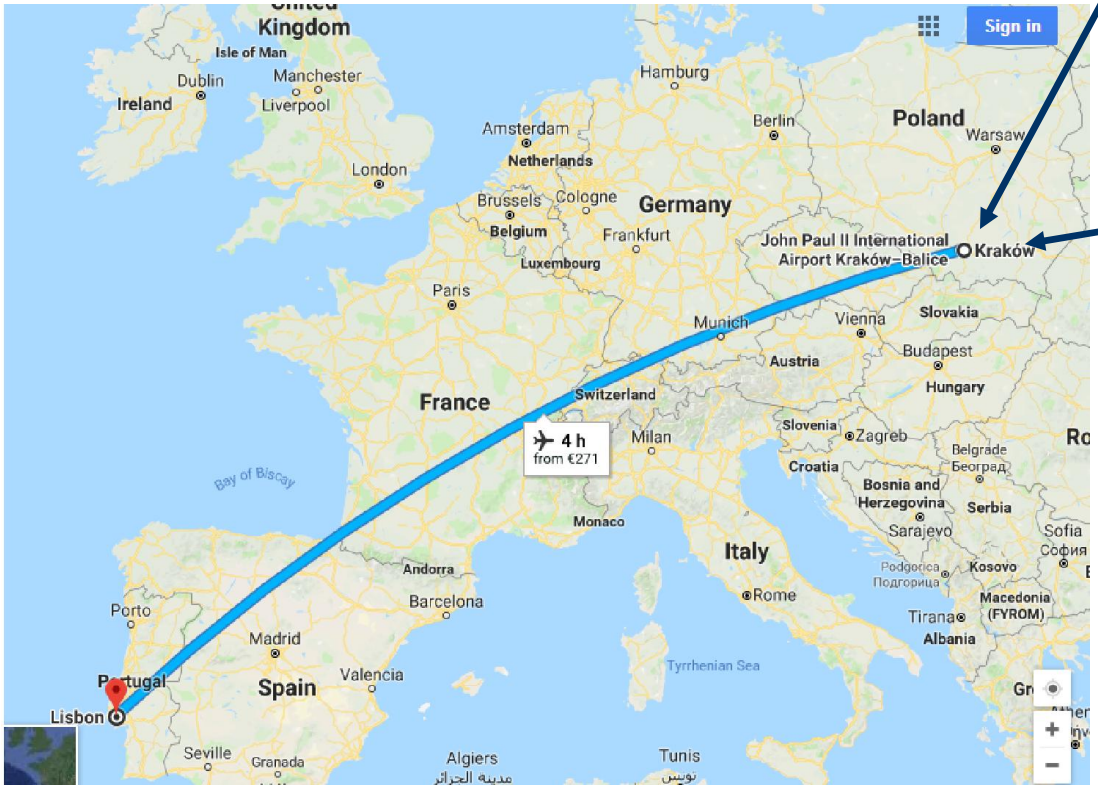


Pawel Kulakowski, AGH Univ. of Sc. And Tech., Krakow, Poland

kulakowski@kt.agh.edu.pl

# Where I work

AGH Univ. Of Sc. And Tech.




Jagiellonian Univ.

# Talk outline

1. Nanocommunications:
   motivation and overview of possible approaches

2. Theory of FRET phenomenon

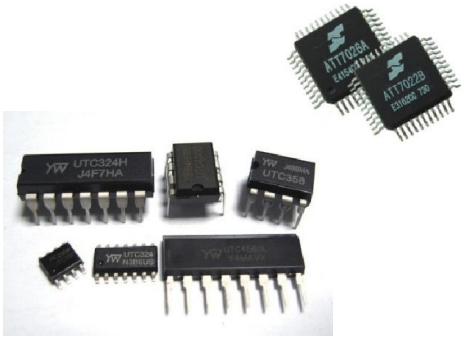
3. Experiments

4. Going from basic science to applications:
   simulation results

5. Open issues and conclusions

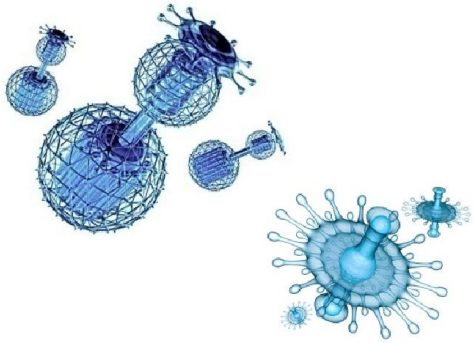
# Nanocommunication origins

## ELECTRONICS

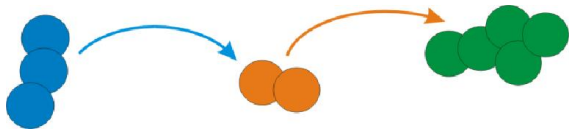


## COMMUNICATIONS


## NANOTECHNOLOGY



## NANO-COMMUNICATIONS



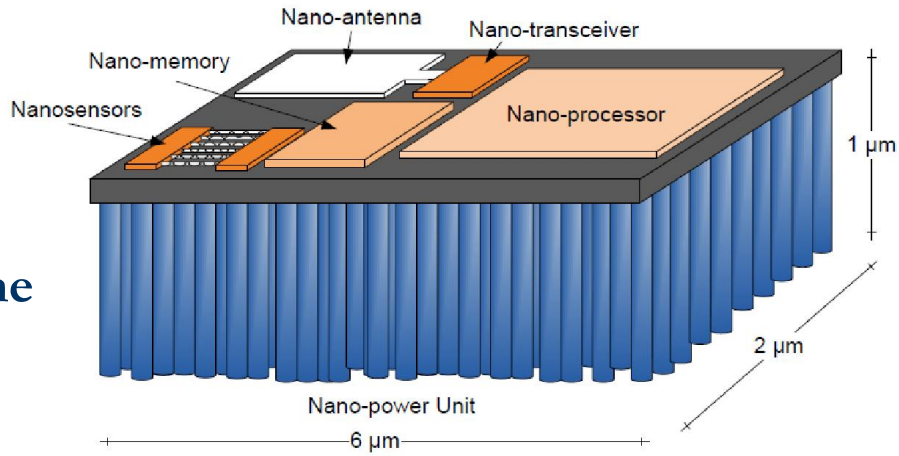


I.F. Akyildiz, F. Brunetti, C. Blazquez, "NanoNetworking: A New Communication Paradigm", Computer Networks, 2008.

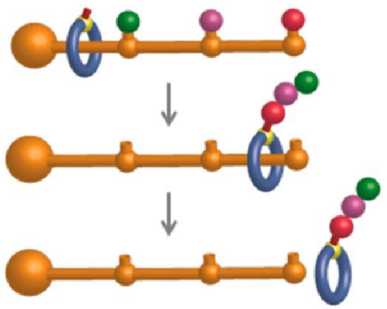
# Possible approaches

## 1. Miniaturization (*top-down*)

- new materials:
  carbon nanotubes and graphene
- 0.1-10 THz band



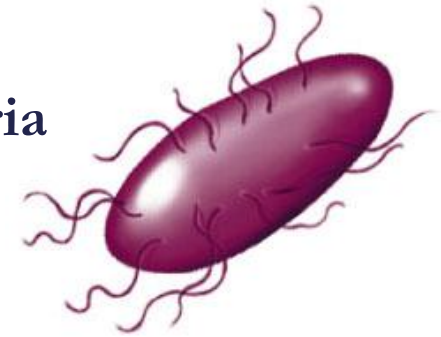

## 2. Building from single molecules (*bottom-up*)

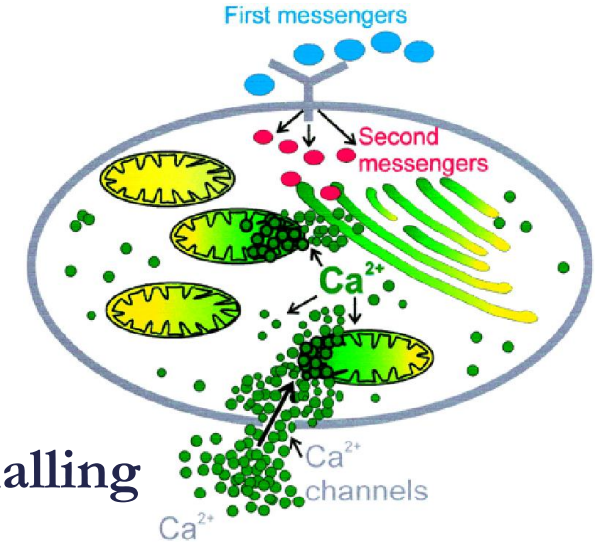


## 3. Molecular communication (arising from *bio-hybrid approach*)

# Molecular mechanisms considered

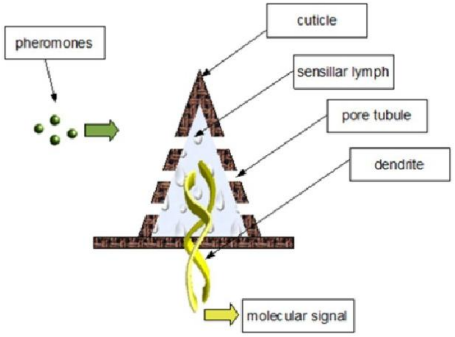
flagellated bacteria



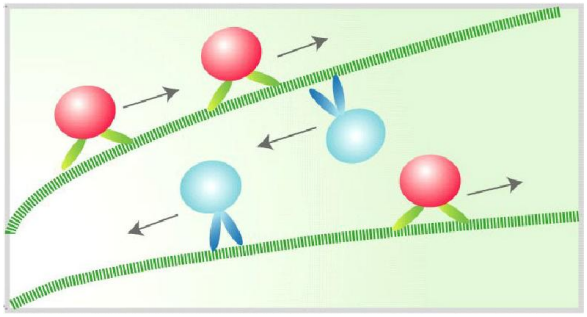



calcium ions signalling

pheromones propagation




molecular motors

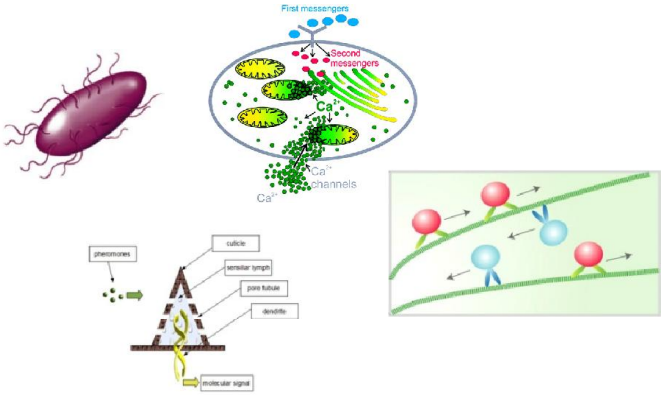




T. Nakano, A. W. Eckford, and T. Haraguchi, Molecular Communications., Cambridge Univ. Press, 2013

# Signal propagation speed in molecular comm.

## Molecular mechanisms




$< 50\ \mu m/s\ (5\times10^{-5}\ m/s)$

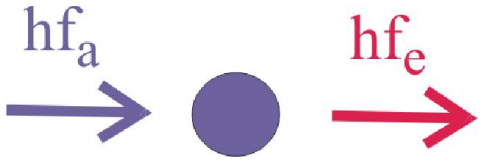
**Förster Resonance Energy Transfer (FRET)**

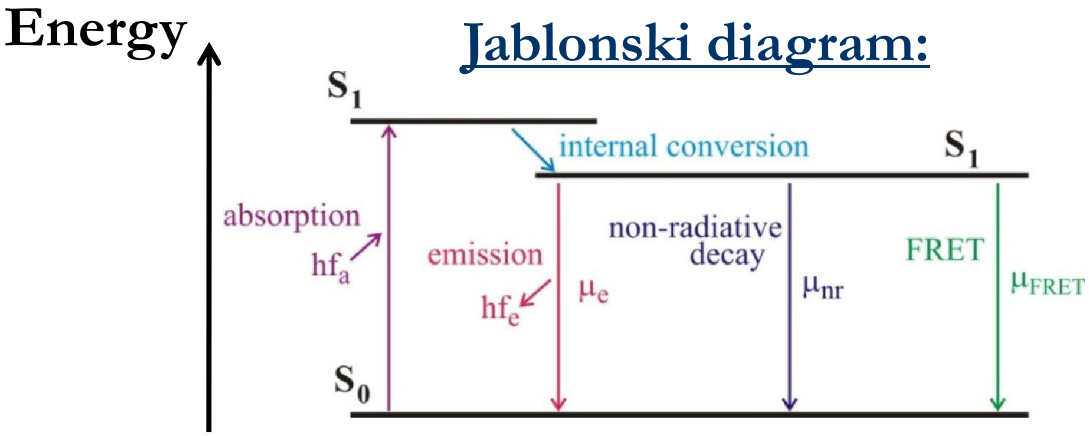

$\approx 1\ m/s$

# Theory

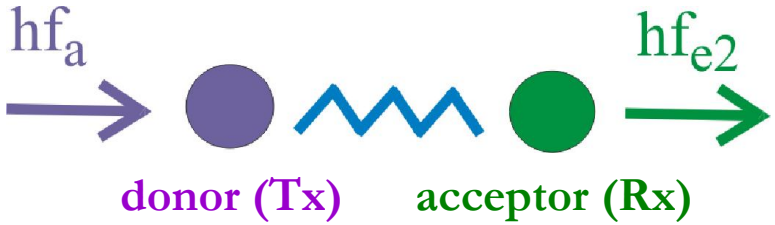
# Förster Resonance Energy Transfer (FRET)

EXCITATION, EMISSION:




EXCITATION, **FRET**, EMISSION:




**FRET efficiency:**

$$E = \frac{R_0^{\,6}}{r^6 + R_0^{\,6}}$$

**Energy:**

$$hf_a > hf_e > hf_{e2}$$

**$R_0$ (Förster radius) = 3÷9 nm**

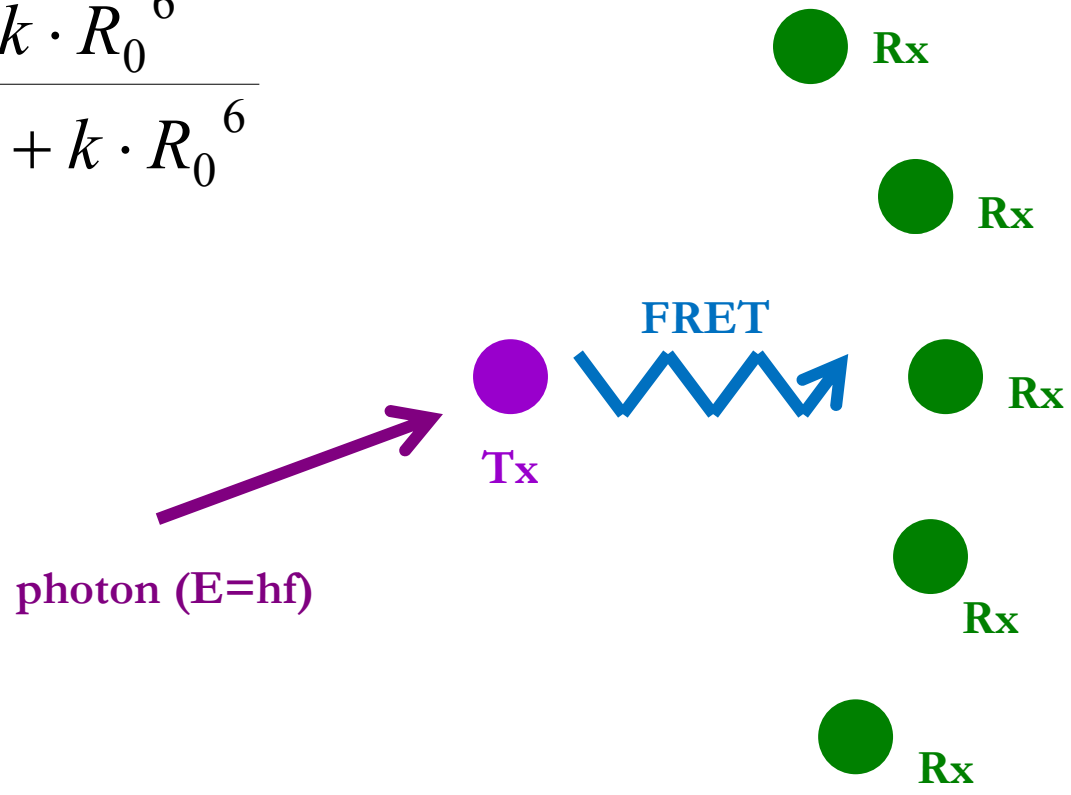


T. Förster "Zwischenmolekulare Energiewanderung und Fluoreszenz", Annalen der Physik, 1948.

# FRET efficiency

**with *k* equally distant acceptors:**

$$E = \frac{k \cdot {R_0}^6}{r^6 + k \cdot {R_0}^6}$$






K. Solarczyk, et al., "Nanocommunication via FRET with DyLight dyes using Multiple Donors and Acceptors", 2016.

# FRET efficiency

**with *n* donors and *m* acceptors (MIMO):**

$$E_{n,m} = 1 - \prod_{k=1}^{n} \left( 1 - \frac{R_0^6 \sum_{i=1}^{m} \frac{1}{r_{ki}^6}}{1 + R_0^6 \sum_{i=1}^{m} \frac{1}{r_{ki}^6}} \right)$$

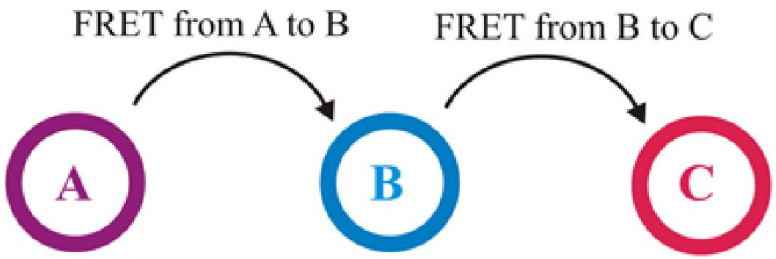

**ON-OFF modulation scheme:**

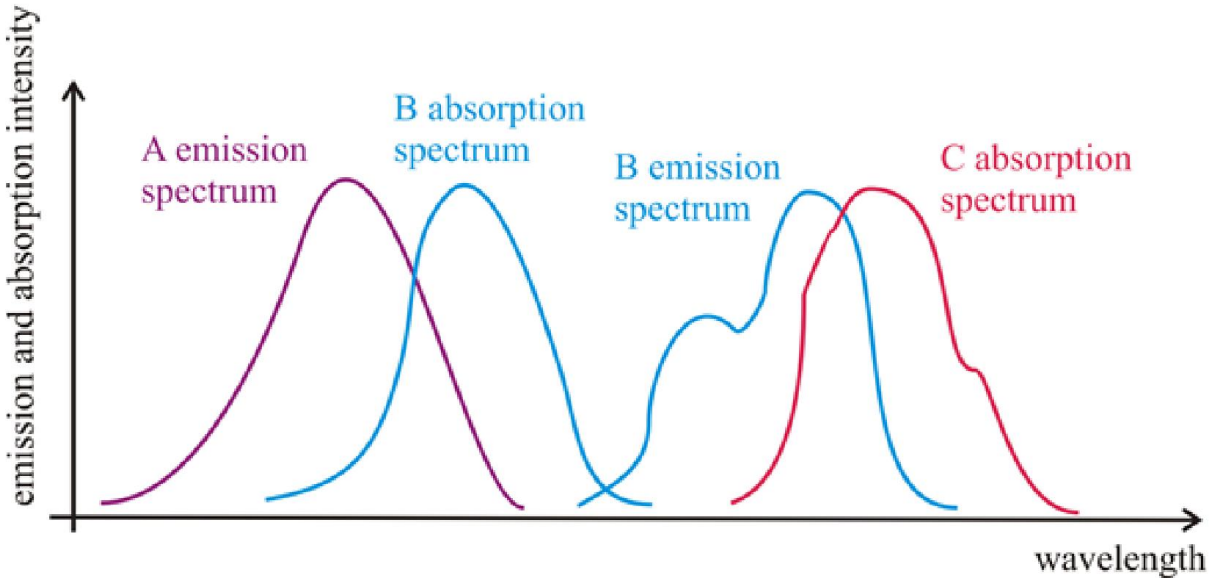
- bit ‘0’ = no signal
- bit ‘1’ = excitation of all Txs, FRET



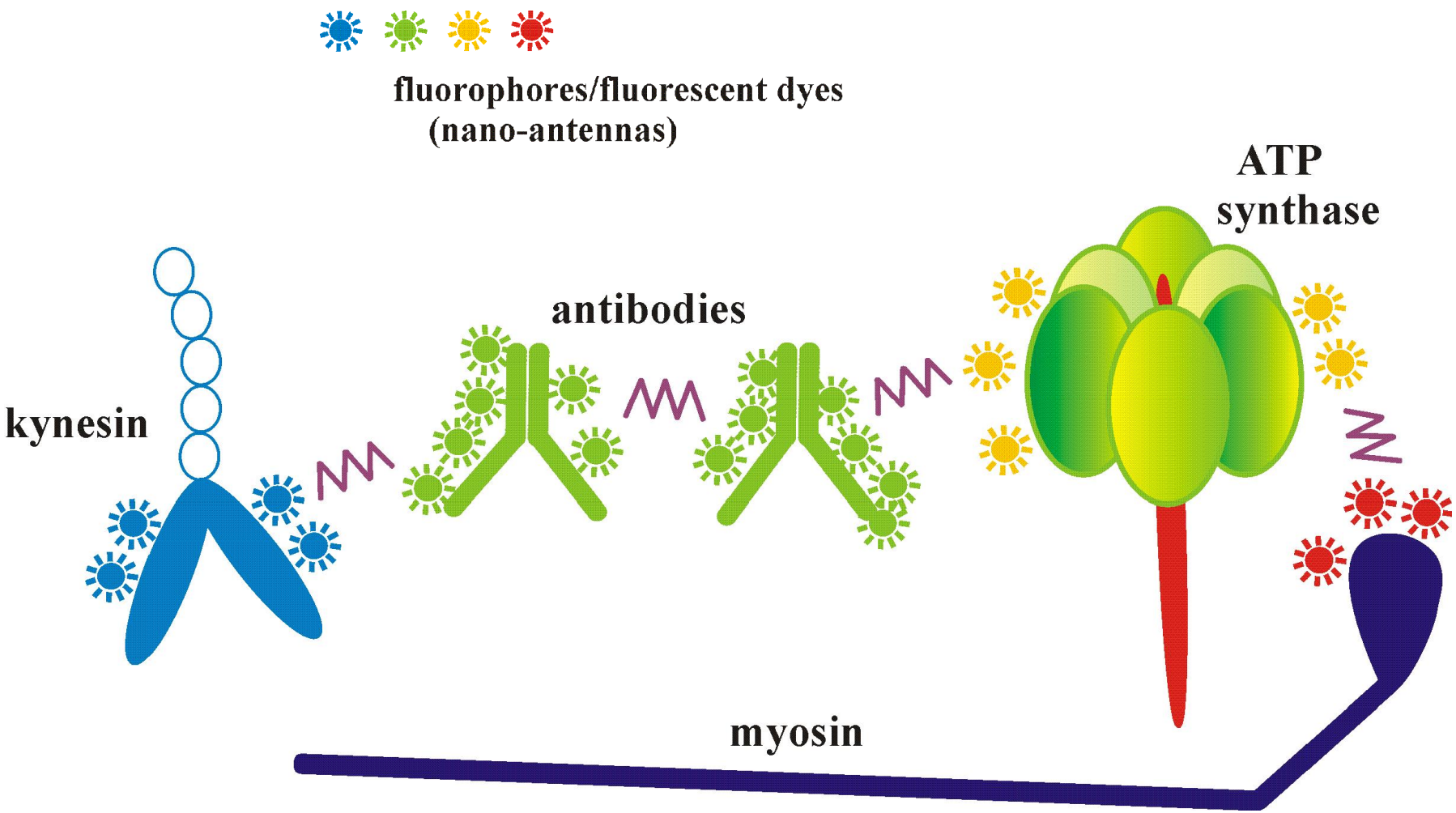
M. Kuscu, et al., "A Physical Channel Model and Analysis for Nanoscale Communications …", 2012.

# Multi-hop FRET



# Communicating nanomachines



# Transmission …

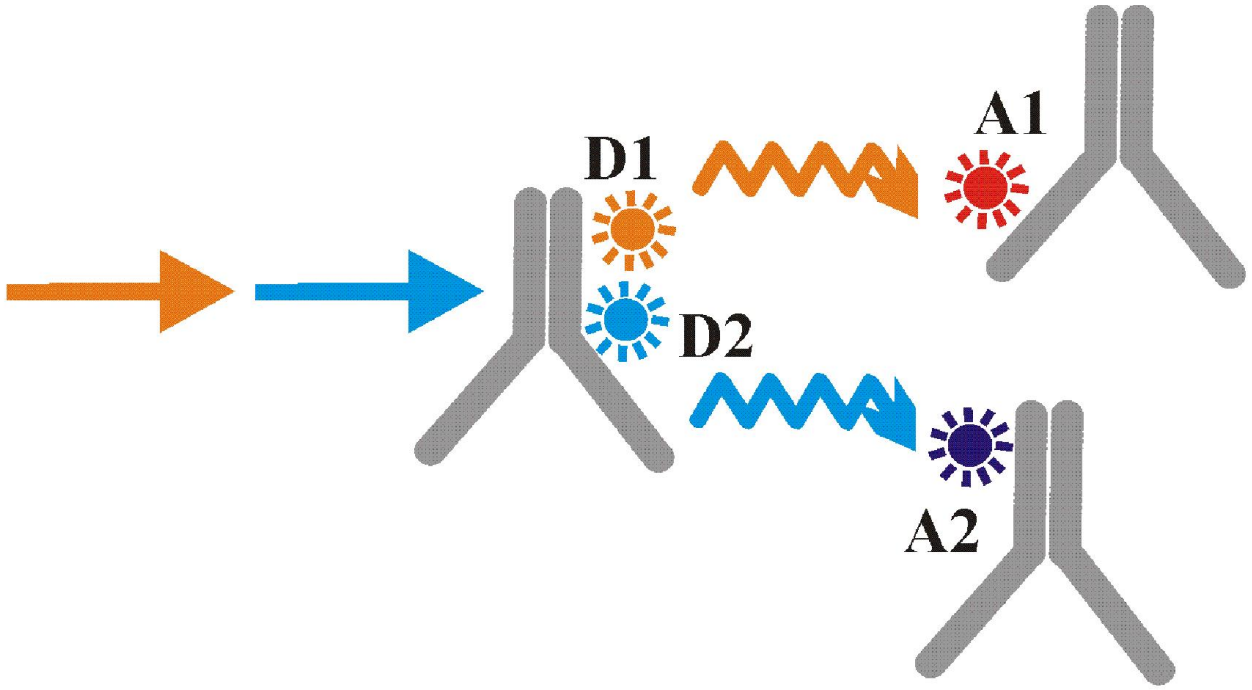
**ON-OFF modulation scheme**

**MIMO-FRET**

## … and routing?

# Routing options in FRET-based nano-networks

## 1. Proteins with a few different fluorescent dyes:

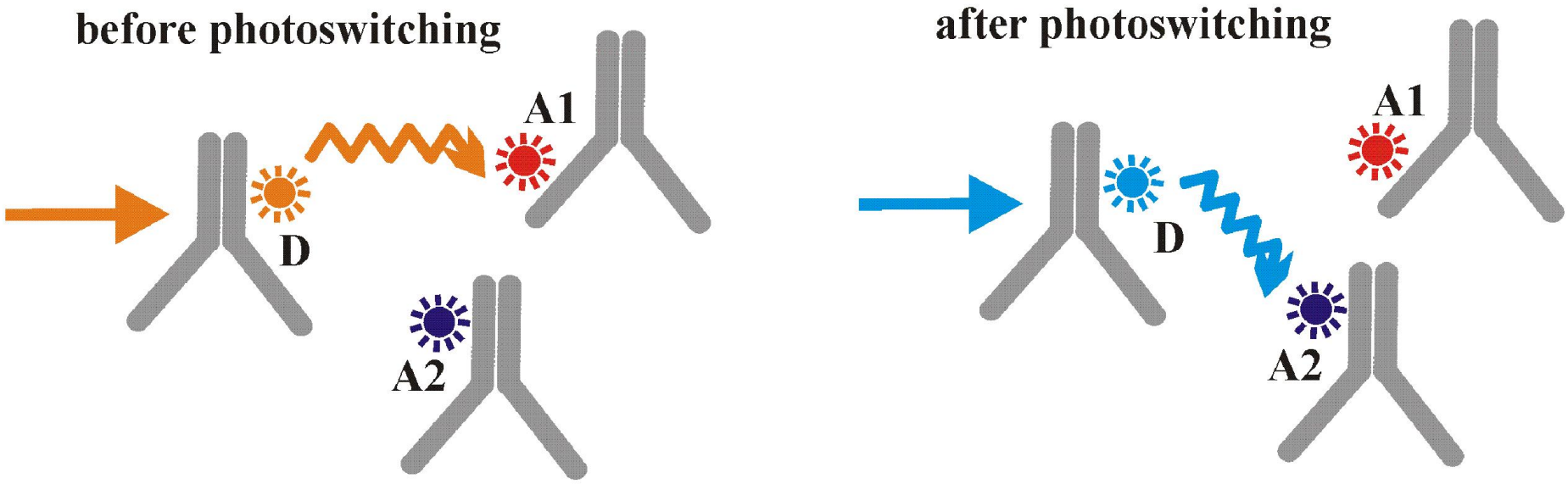





P. Kulakowski, K. Solarczyk, K. Wojcik, Routing in FRET-Based Nanonetworks, IEEE Communications Magazine, 2017.

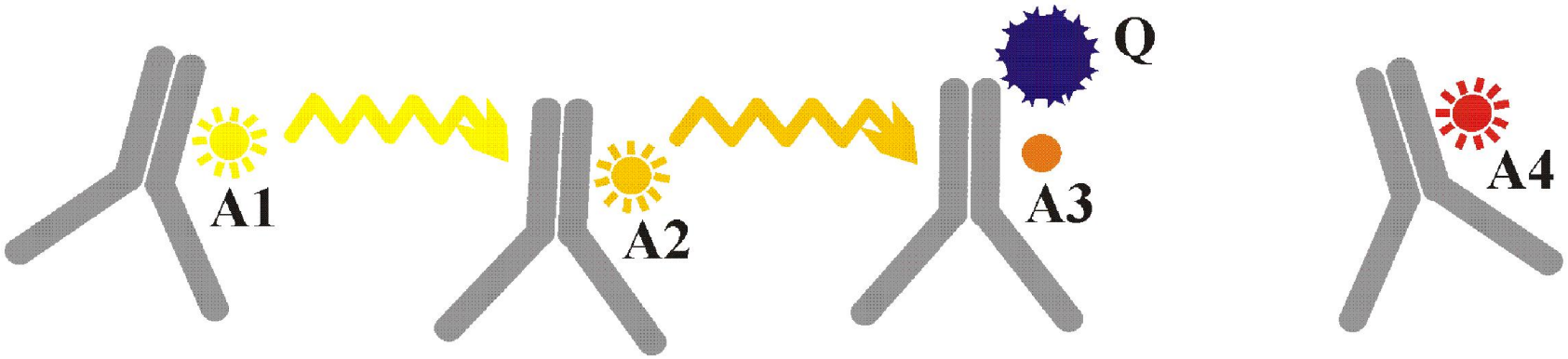
# Routing options in FRET-based nano-networks

## 2. Photoswitchable fluorophores:



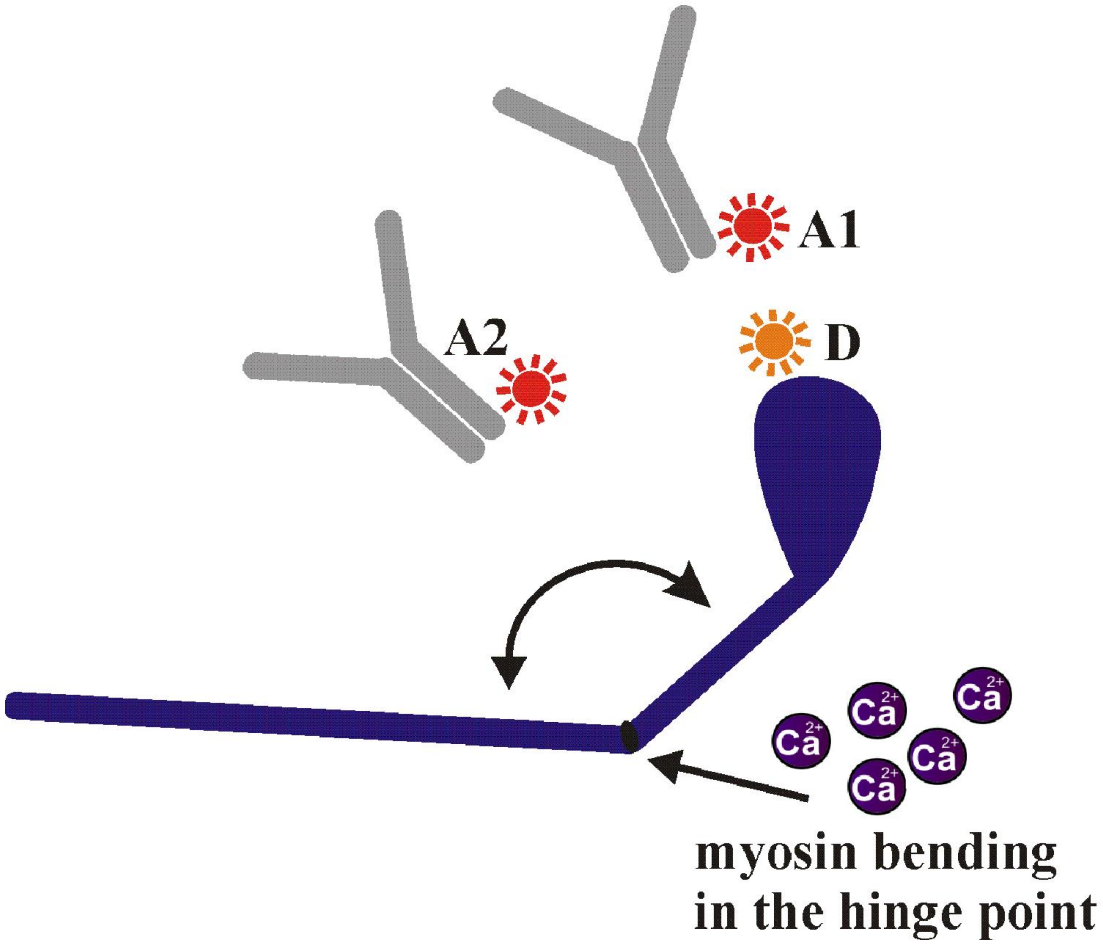
# Routing options in FRET-based nano-networks

## 3. Quenchers:



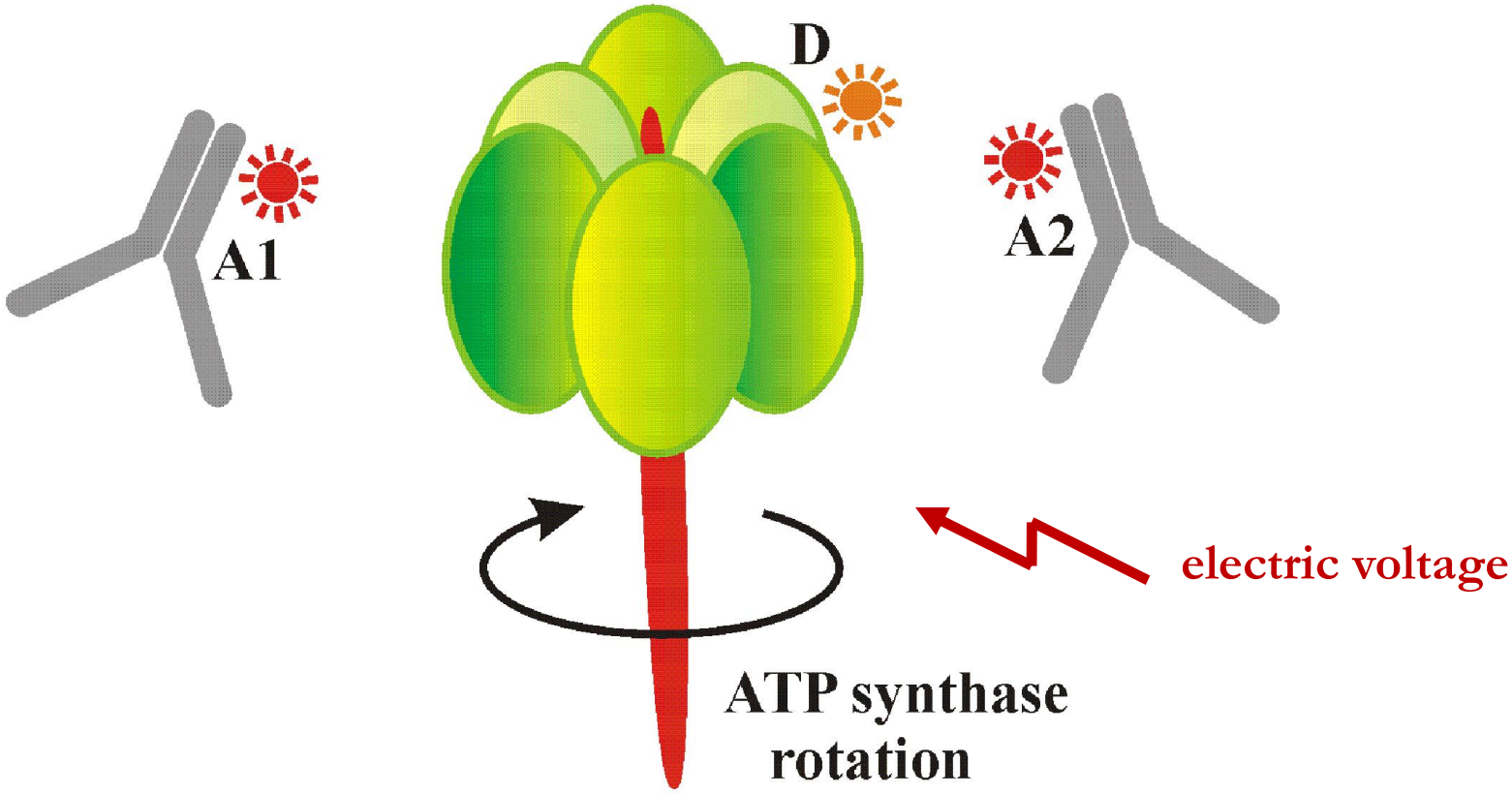
# Routing options in FRET-based nano-networks

## 4. Proteins with changeable shape:



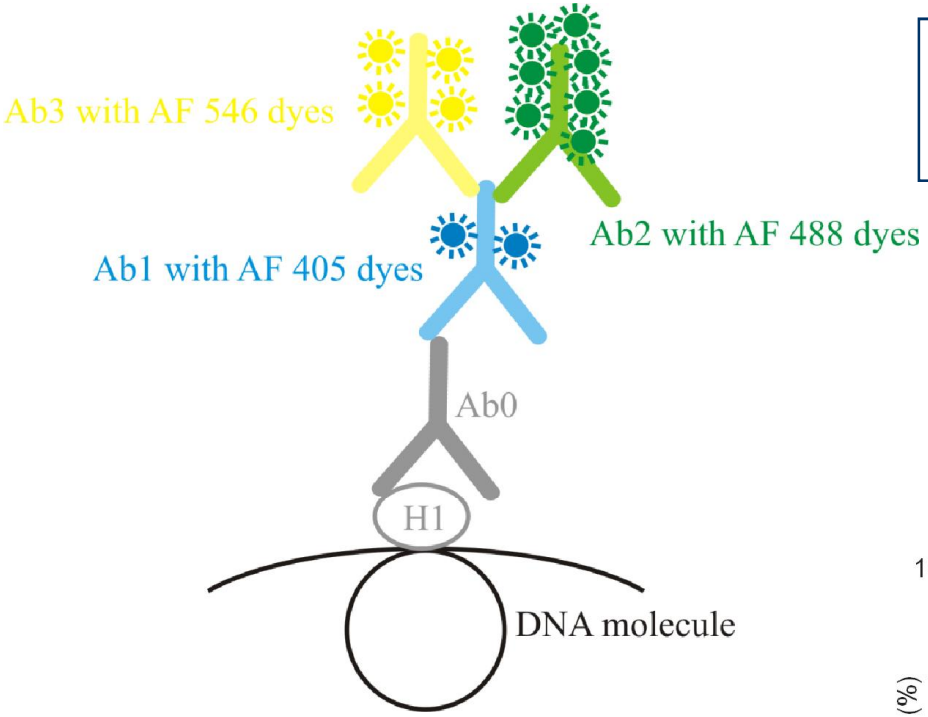
# Routing options in FRET-based nano-networks

## 5. ATP synthase:



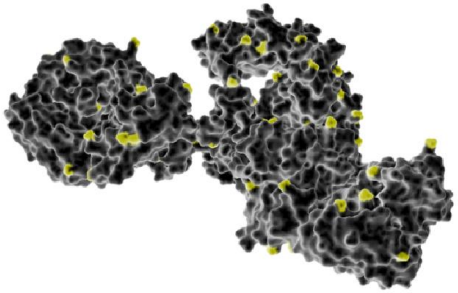
# Experiments

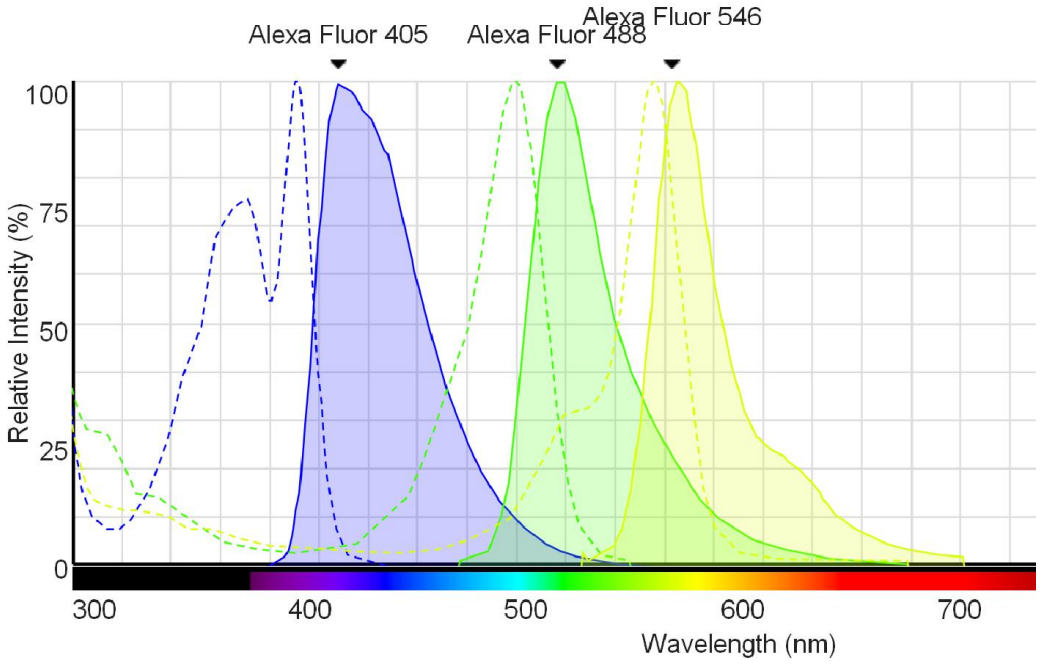
# A network of antibodies (Ab) and Alexa Fluor (AF) dyes




antibody (protein) = nano sensor
AF dye = nano transceiver/antenna

antibodies in the experiment:
**immunoglobulin G**



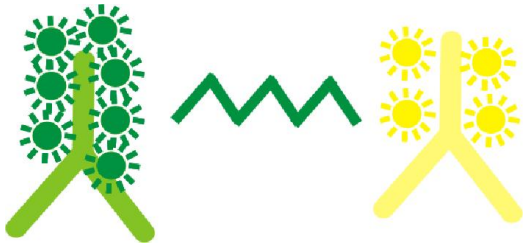


# MIMO-FRET measurements

AF405→AF488 - MIMO (1,7):

**E = 14 %**

AF488→AF546 - MIMO (1,4):



**E = 46 %**

AF405→AF546 - MIMO (1,4):

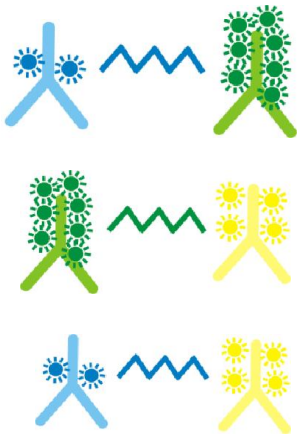
**E = 9 %**



K. Wojcik, et al., Measurements on MIMO-FRET nano-networks based on Alexa Fluor dyes, IEEE Trans. on Nanotech., 2015.

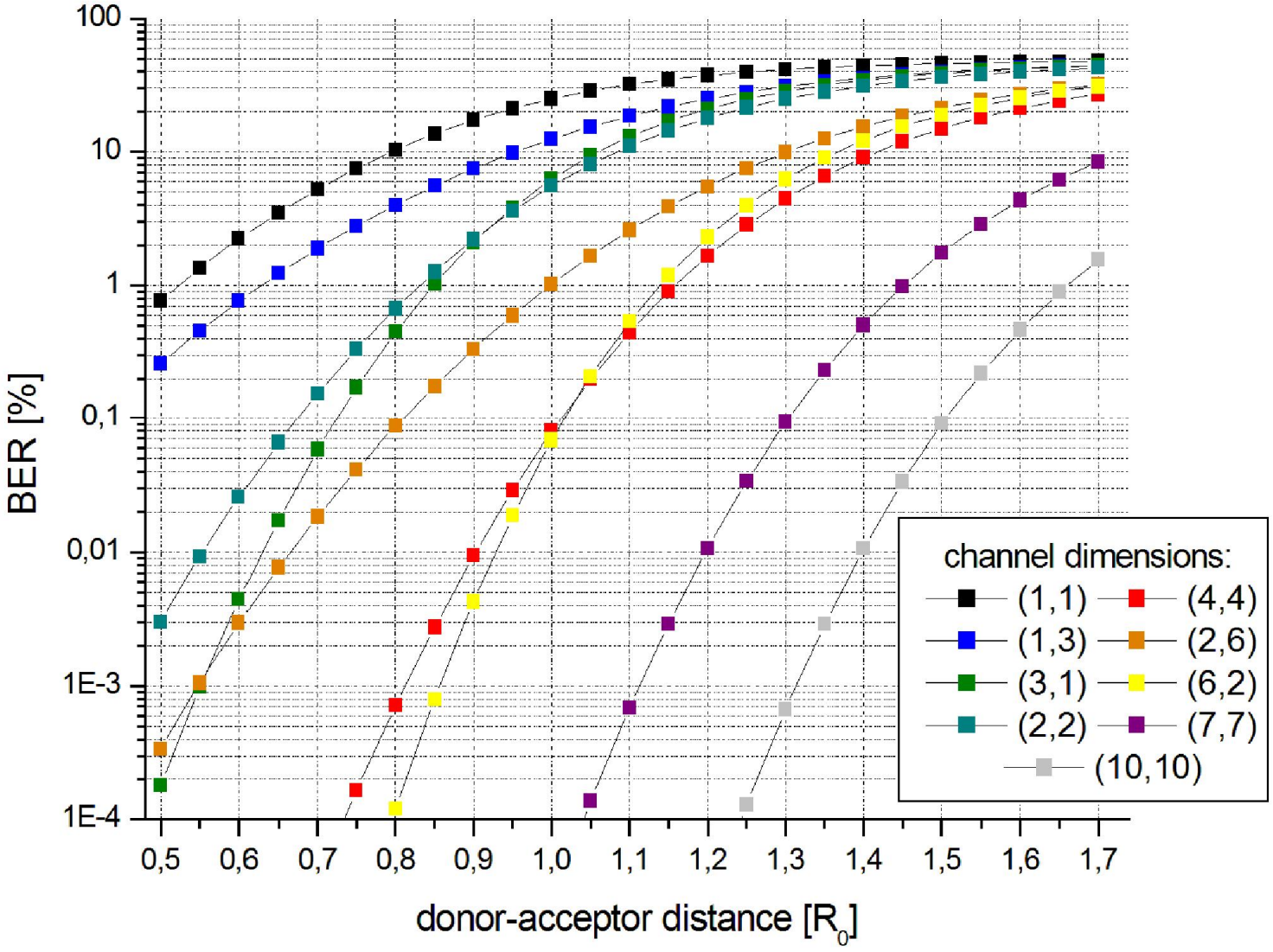
# BER calculations for MIMO (1,m) and (n,m)

$$\mathrm{BER}_{n,m} = 0.5 \cdot (1 - E)^n$$

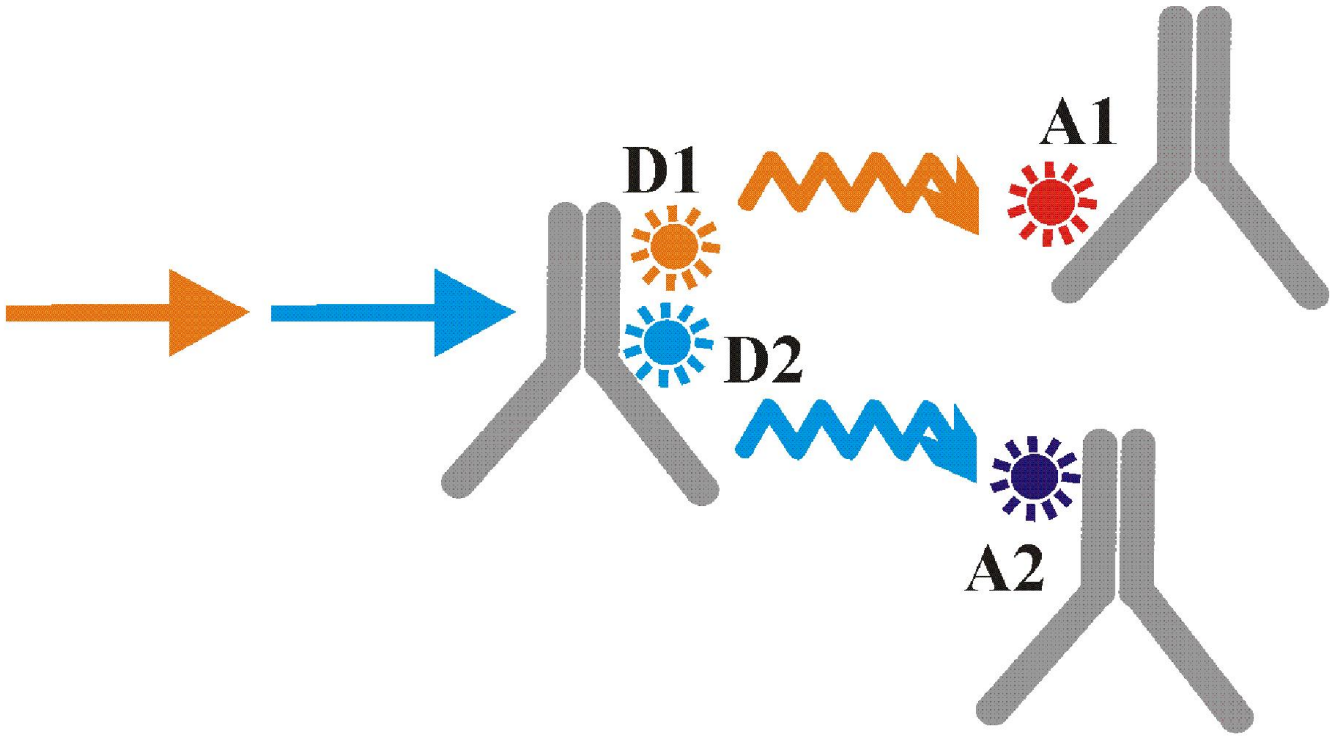


| | measured FRET efficiency | BER for (1,m) channel | BER for (n,m) channel |
|---|---|---|---|
| AF405→AF488 | **14 %** | 43 % | **37 %** |
| AF488→AF546 | **46 %** | 27 % | **0.7 %** |
| AF405→AF546 | **9 %** | 45.5 % | **41 %** |

# Theoretical BER curves for MIMO (n,m) channels

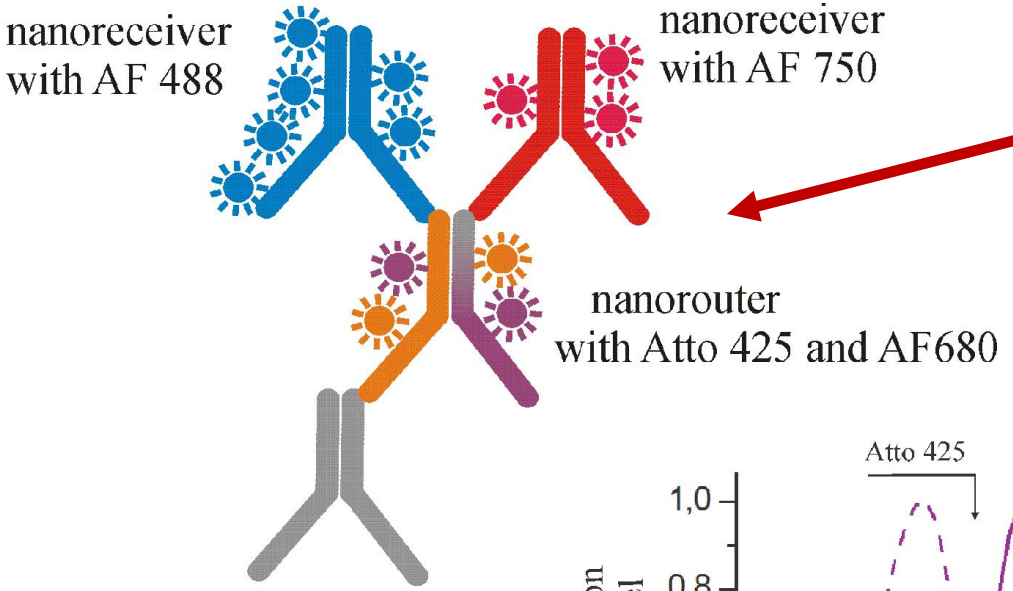


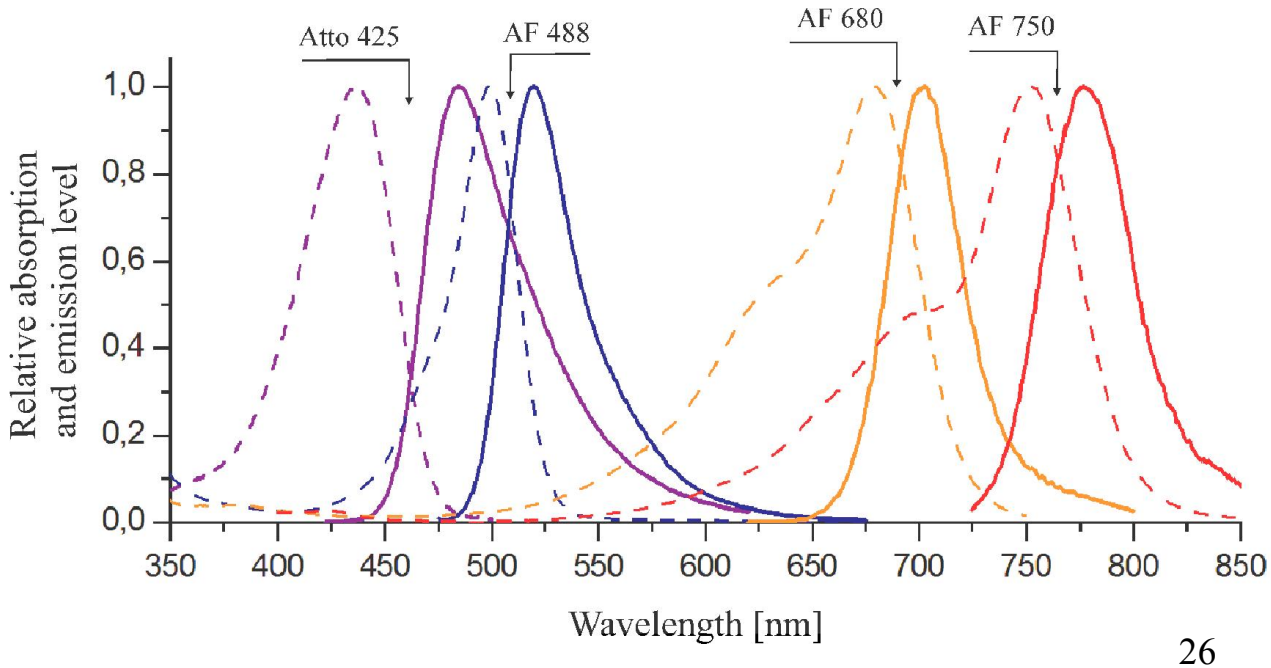
# Routing measurements



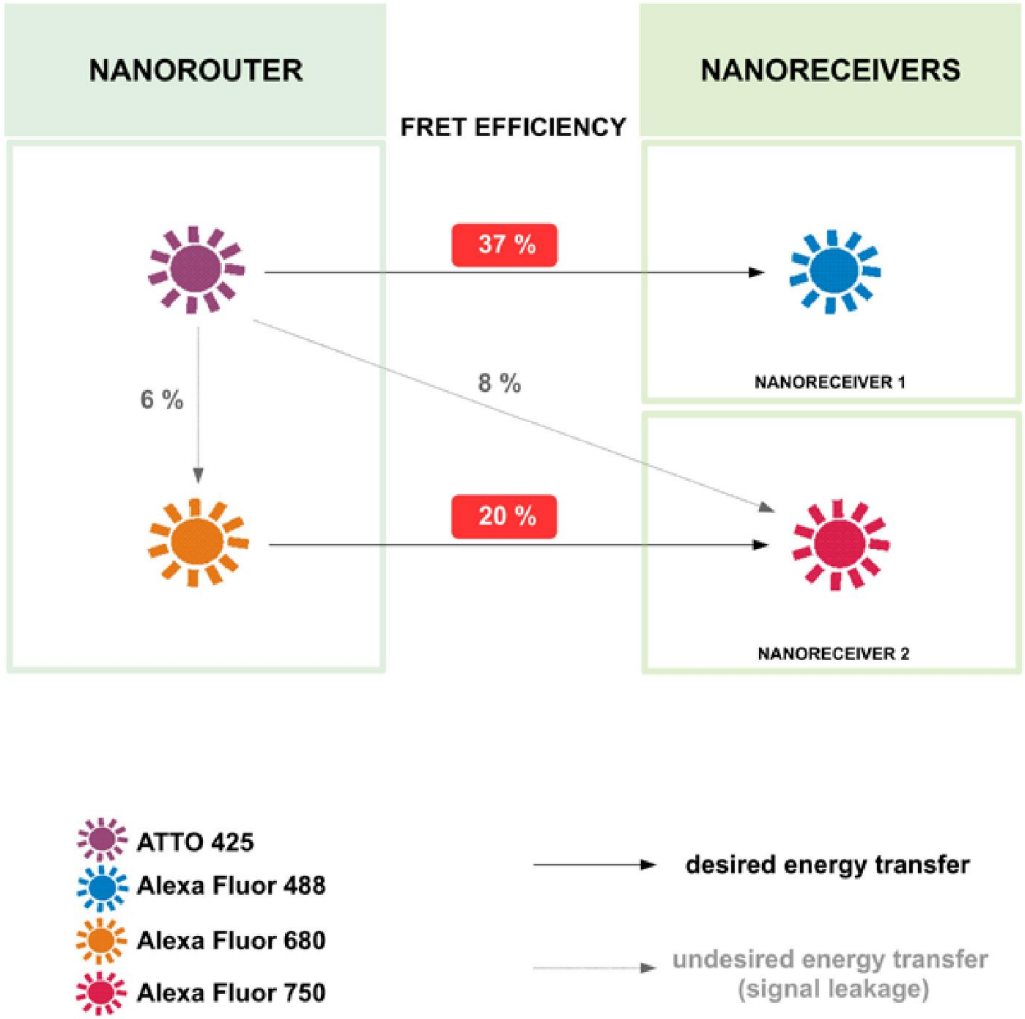
# Measurements with Leica confocal microscope

$10^8$ nanonetworks examined



# Measurements with Leica confocal microscope





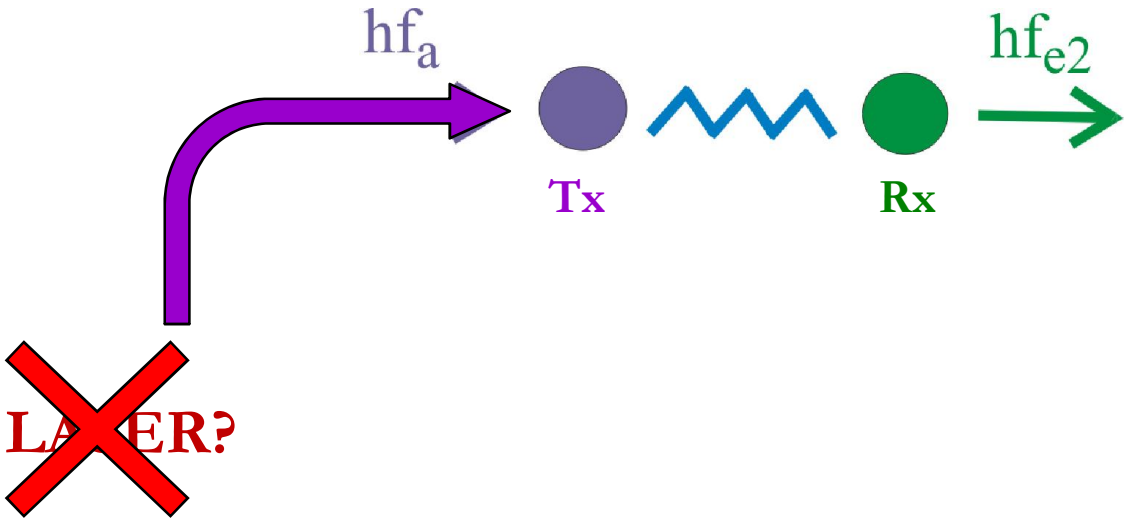

P. Kulakowski, K. Solarczyk, K. Wojcik, Routing in FRET-Based Nanonetworks, IEEE Communications Magazine, 2017.

# Simulations

## Going from basic science to applications

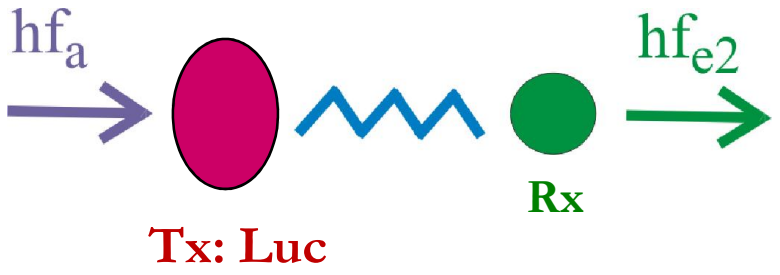
# Question 1: How to provide INPUT signals?

EXCITATION, **FRET**, EMISSION:



# Question 1: How to provide INPUT signals?

CHEMICAL
EXCITATION, **FRET**, EMISSION:



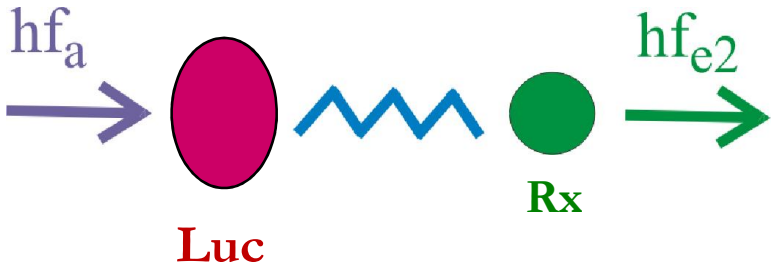

**Instead:**

**LUCIFERASE**

(***a molecule that can be excited via a chemical reaction***)

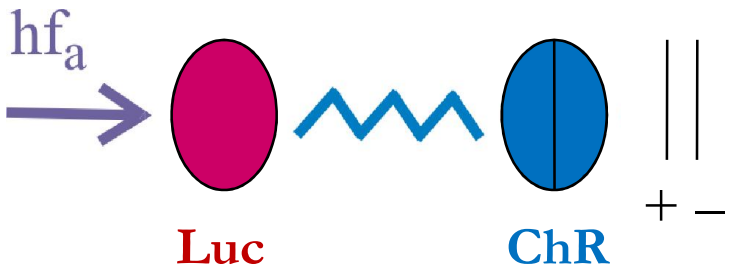
# Question 2: How to collect OUTPUT signals?

CHEMICAL
EXCITATION, **FRET**, EMISSION:

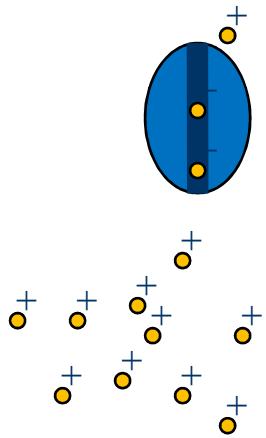


# Question 2: How to collect OUTPUT signals?

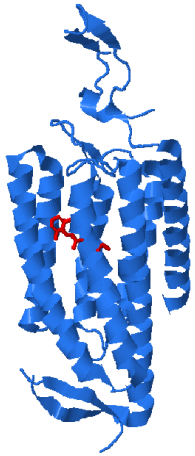
CHEMICAL EXCITATION, **FRET**, VOLTAGE CHANGE:



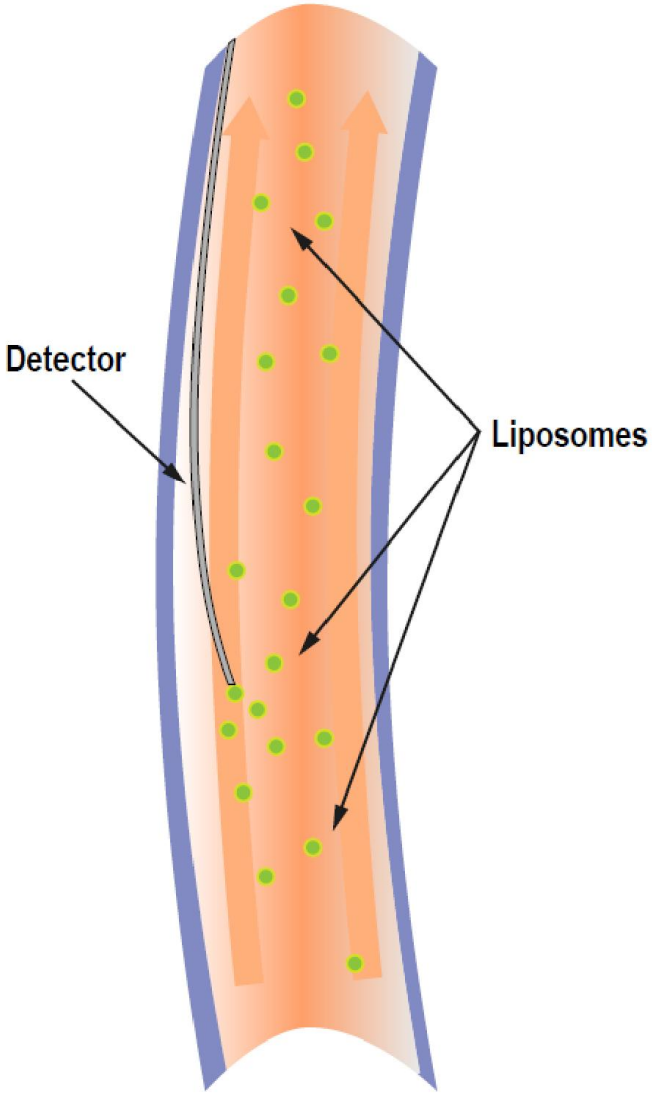

**ChR:**

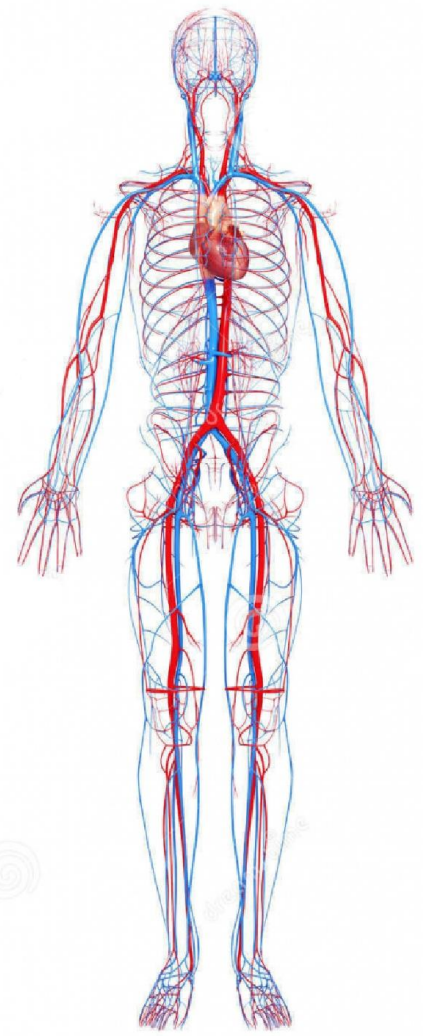


**CHANNELRHODOPSIN**
(***after excitation,***
***opens a channel for cations***)

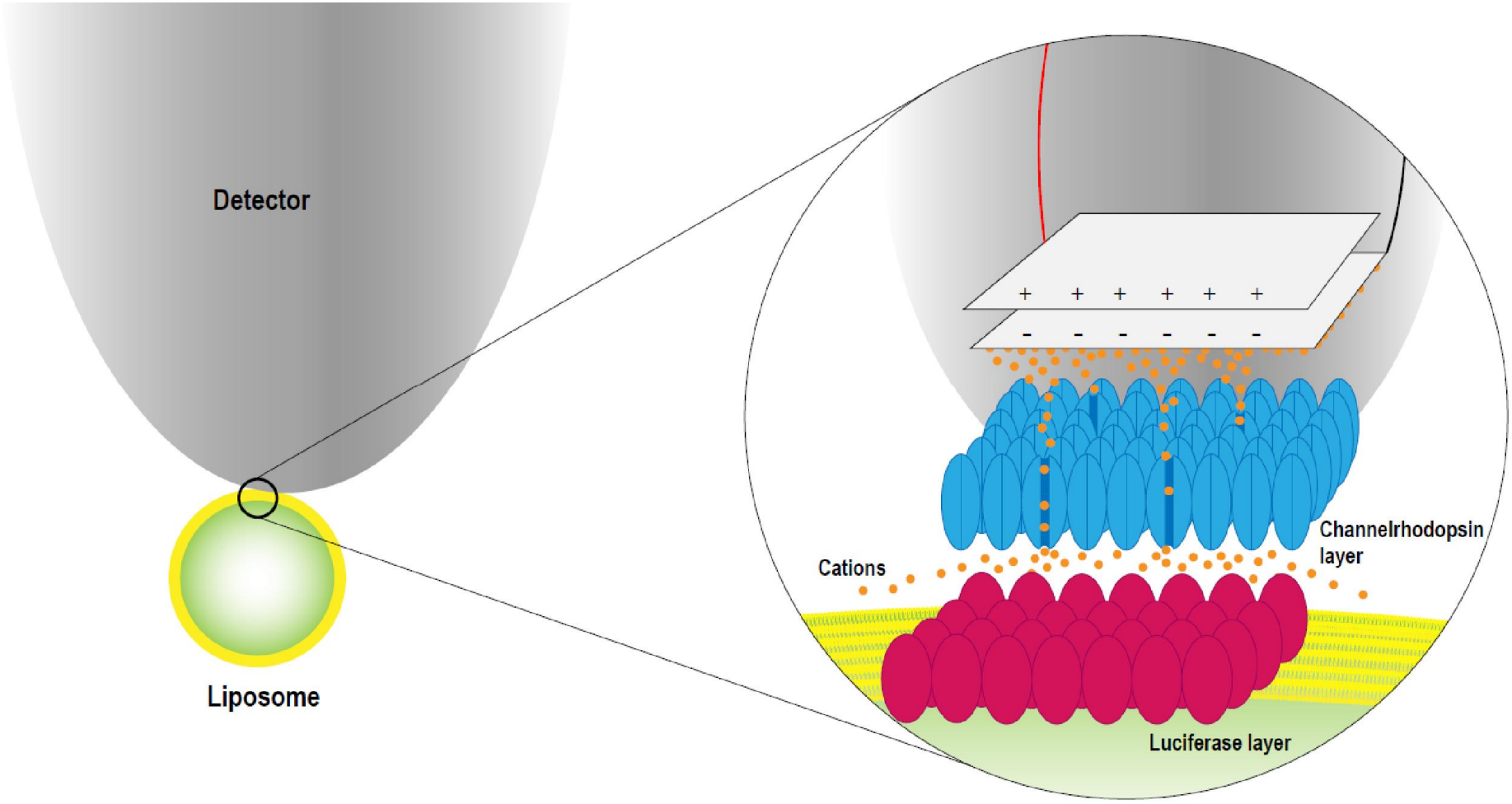


# In-body medical system



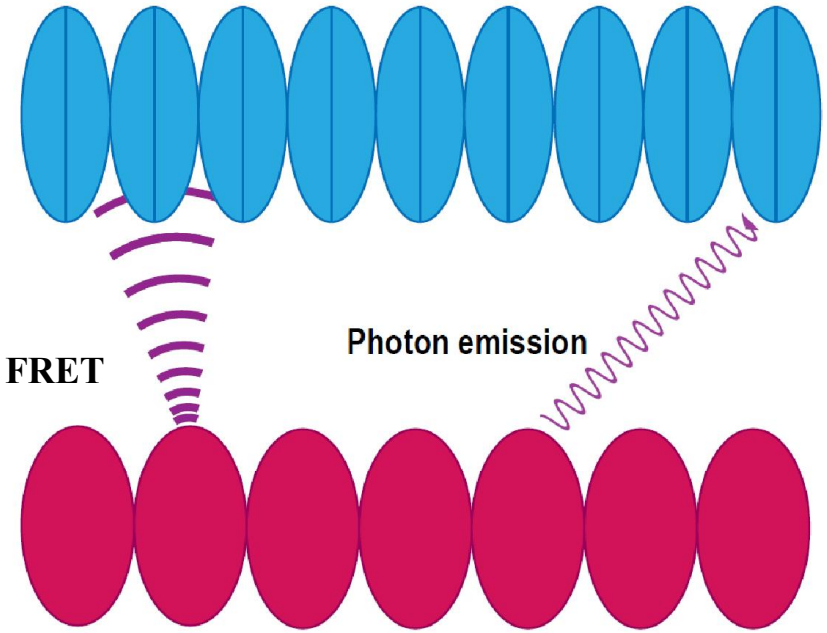
# FRET-based communication





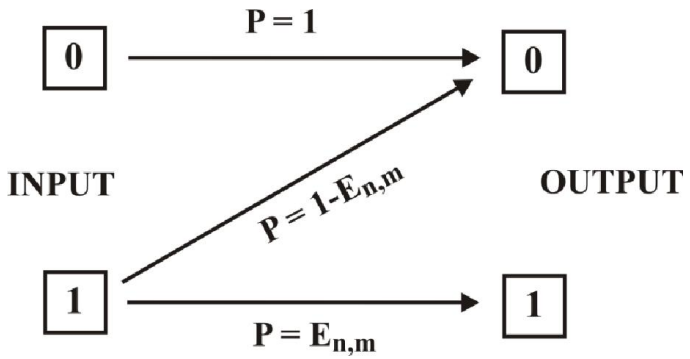

J. Kmiecik, K. Wojcik, P. Kulakowski, A. Jajszczyk, submitted to IEEE Trans. On NanobioScience.

# Communication with ON-OFF modulation



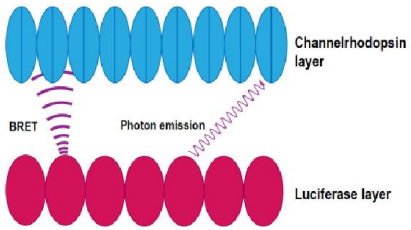

170 nm × 170 nm × 6 nm
(2500 molecules)

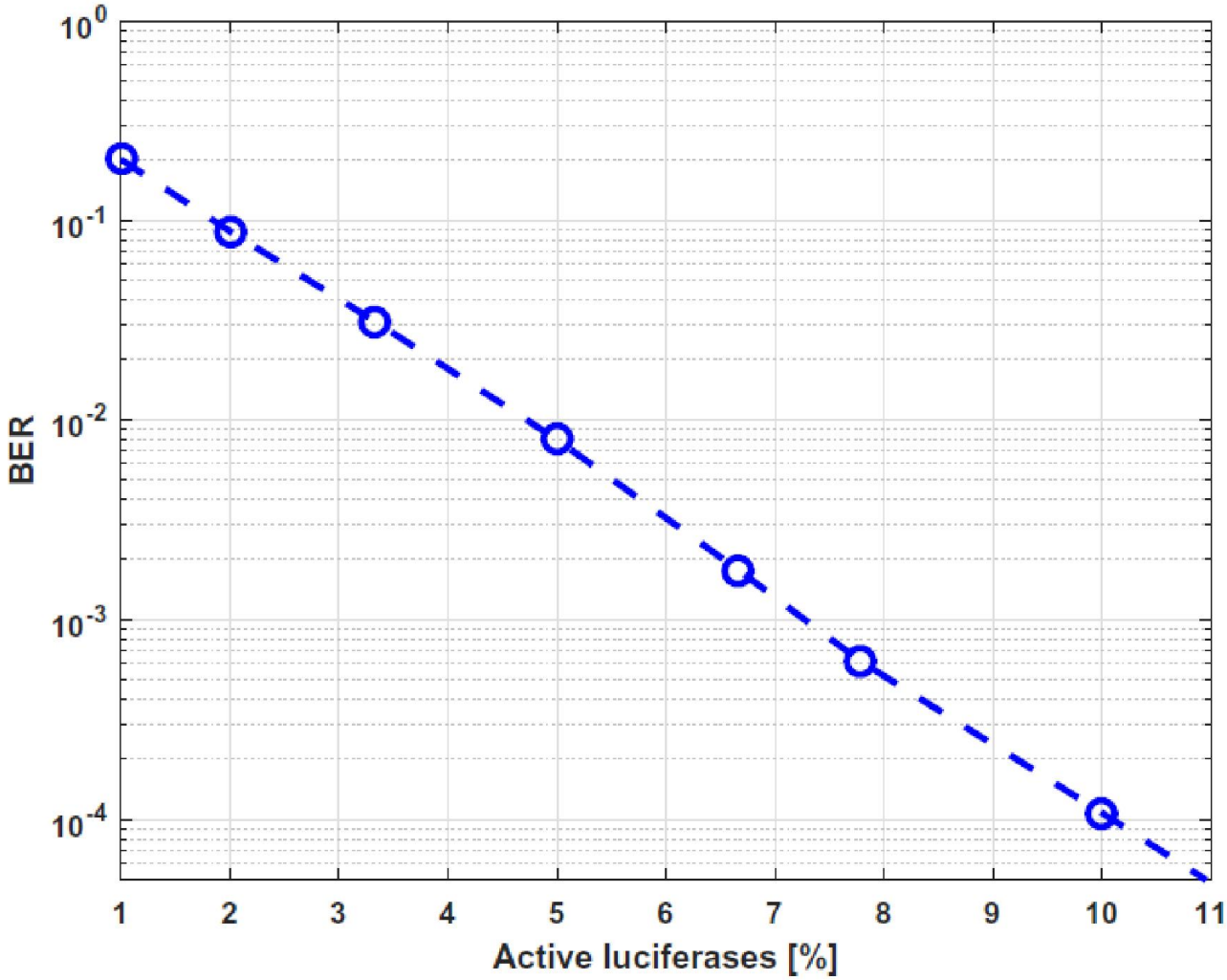
75 nm × 75 nm × 5 nm
(900 molecules)



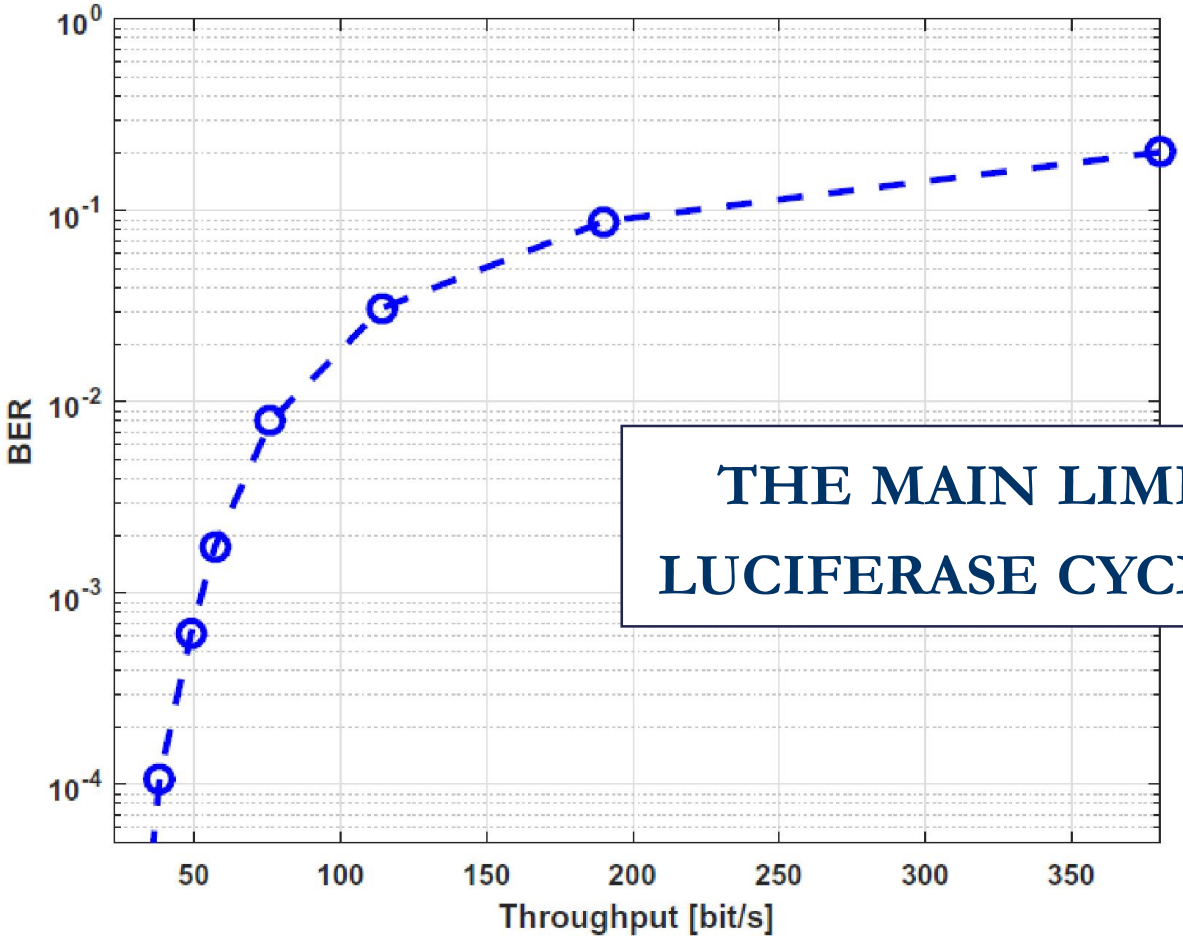

$$\mathrm{BER} = 0.5(1 - E)$$

# Bit error rate



# BER vs. throughput trade-off




**THE MAIN LIMITATION:**
**LUCIFERASE CYCLE = 0.26 s**

# Open issues

1. Routed signal LEAKAGES
   – maybe fluorophores in different EM bands?

2. Switching TIME

3. CONTROL over the transmitter (e.g. providing energy)

4. Nanomachine MOVEMENTS

5. Experiments on SINGLE nanostructures,
   e.g. single molecule FRET?

# Conclusions

1. Nanocommunications – a very hot topic, but requiring stronger BIO-TELE cooperation

2. EM (Terahertz) communications
– suitable rather for MICRO world

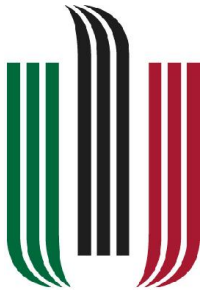
3. Molecular (bio-inspired) approach:
applicable for nanoscale, but quite slow in most cases

4. FRET:
fast, but distance limited, MIMO-FRET required

5. Routing is based on features of specific molecules

6. Nanocommunications is still basic science,
more experiments are welcome!

# Thank you for your attention



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