Applications of Time-Reversal Processing for Planetary Surface Communications

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Abstract

Due to the power constraints imposed on wireless sensor and communication networks deployed on a planetary surface during exploration, energy efficient transfer of data becomes a critical issue. In situations where groups of nodes within a network are located in relatively close proximity, cooperative communication techniques can be utilized to improve the range, data rate, power efficiency, and lifetime of the network [1]. In particular, if the point-to-point communication channels on the network are well modeled as frequency non-selective, distributed or cooperative beamforming can employed [2]. For frequency-selective channels, beamforming itself is not generally appropriate, but a natural generalization of it, *time-reversal communication* (TRC), can still be effective. Time-reversal processing has been proposed and studied previously for other applications, including acoustical imaging [3], electromagnetic imaging [4], underwater acoustic communication [5], and wireless communication channels [6-8].

In this paper, we study both the theoretical advantages and the experimental performance of cooperative TRC for wireless communication on planetary surfaces. We give a brief introduction to TRC and present several scenarios where TRC could be profitably employed during planetary exploration. We also present simulation results illustrating the performance of cooperative TRC employed in a complex multipath environment [9, 10] and discuss the optimality of cooperative TRC for data aggregation in wireless sensor networks [11, 12].

References

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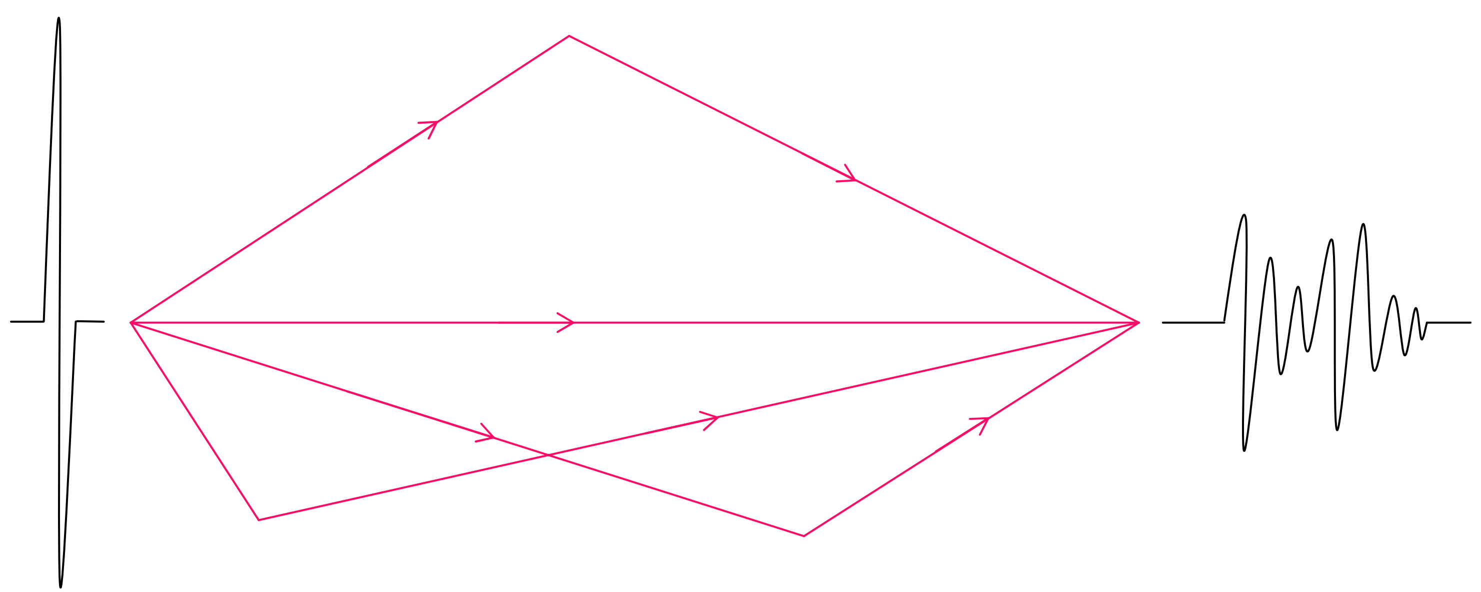
Motivation

- **Efficient Data transfer in low-power broadband sensor and communication networks**
  - **Generalization of distributed beamforming for broadband multipath channels**
  - **Increase link capacity through cooperation**
  - **Focus transmitted power at a particular point in space**
  - **Implications for network capacity and lifetime**

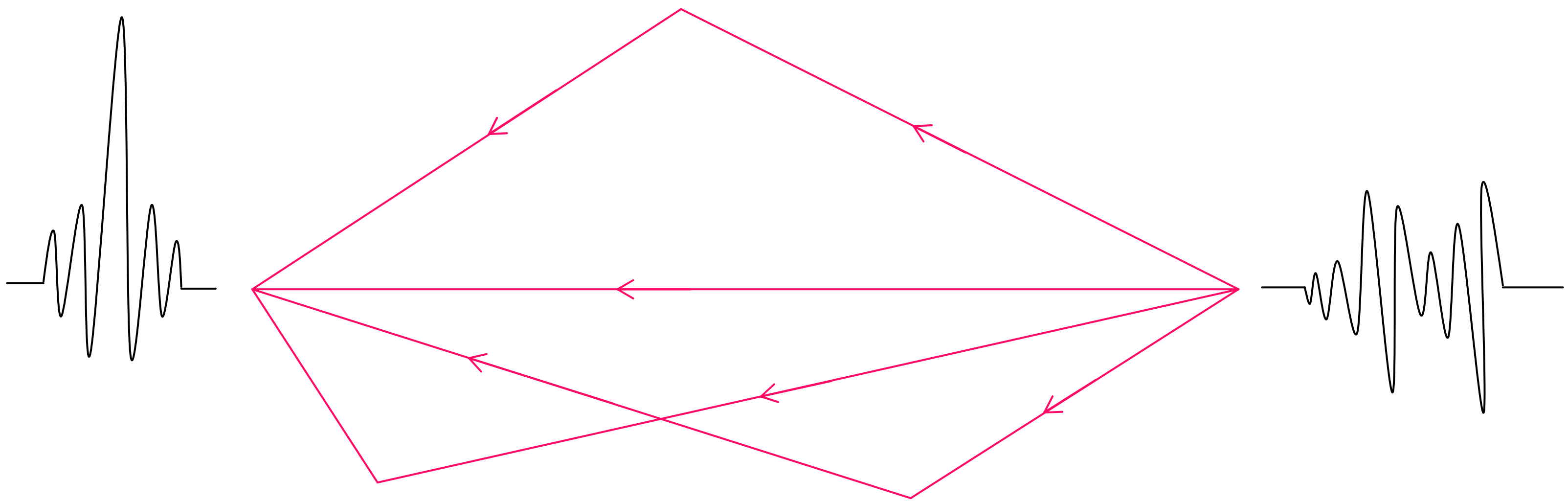
Outline

- Background on time-reversal communication (TRC)
- Properties of TRC
- Simulated performance results
- Possible space applications
- Optimal data aggregation in wireless sensor networks (WSNs)
- Conclusions

Background – Forward-Channel Impulse Response



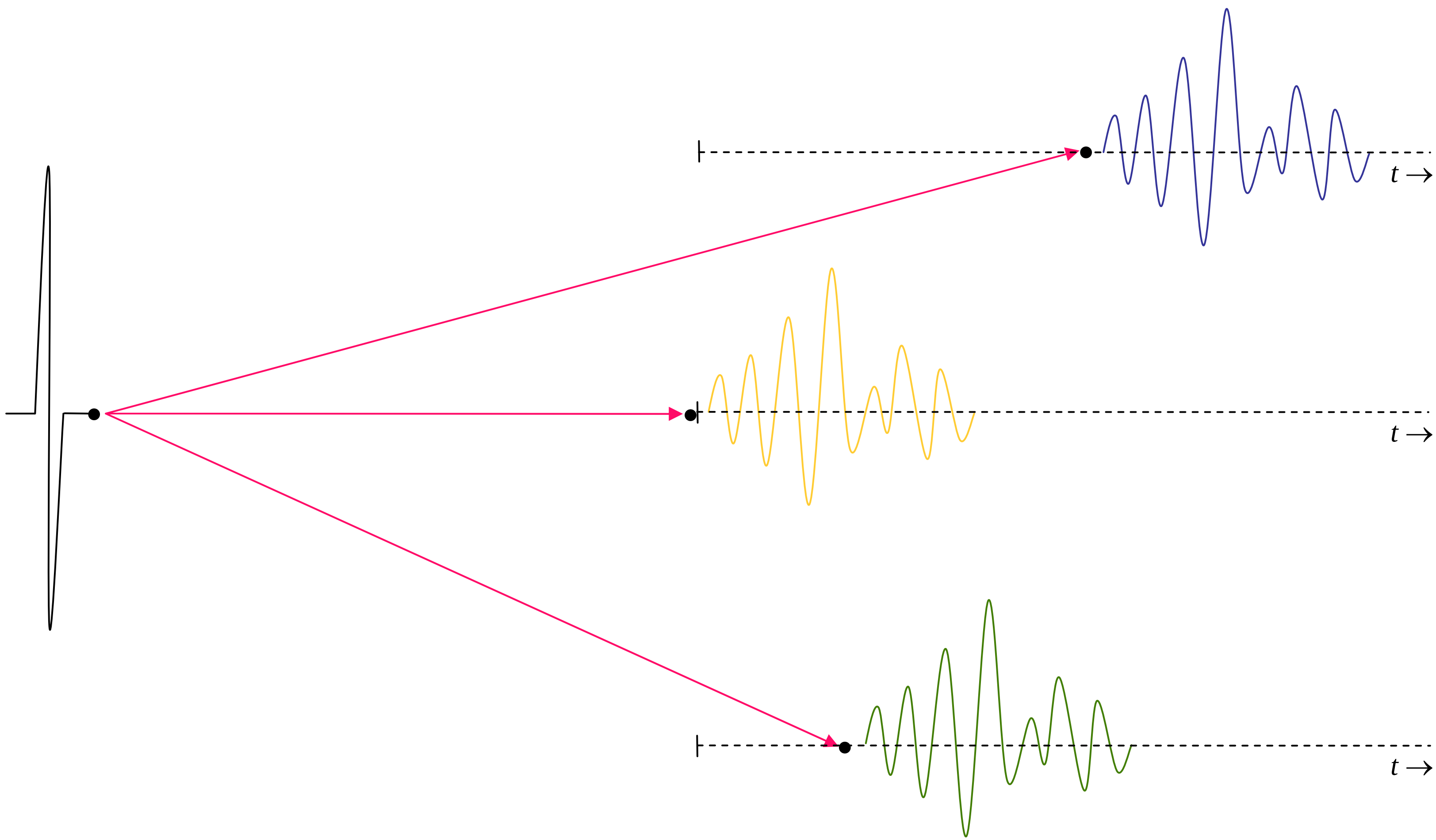
Background – Time-Reversed Channel Response



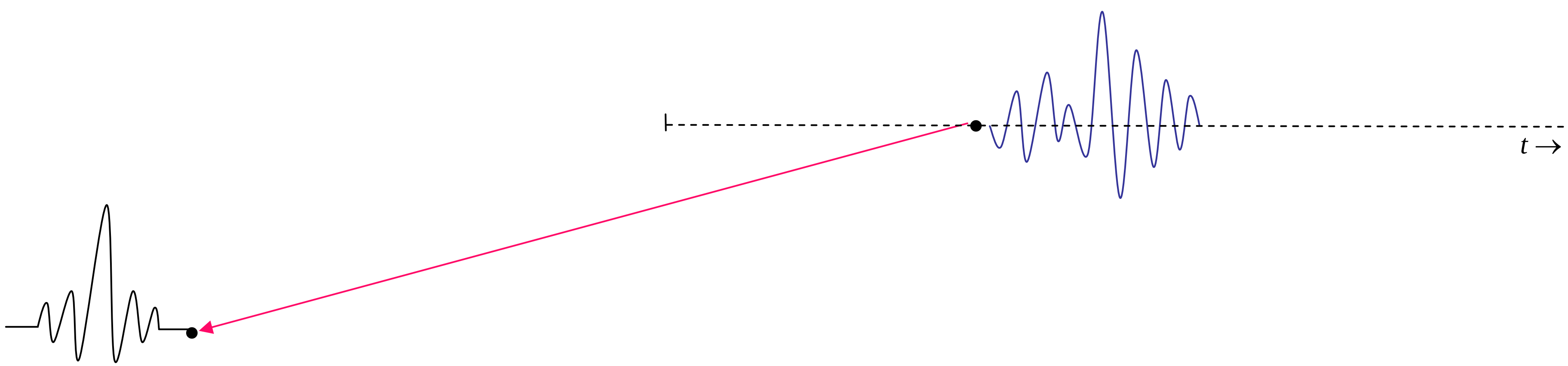
Channel Autocorrelation Function

Time-Reversed Channel Impulse Response

Background – Multiple Receivers



Background – Cooperative Time-Reversal



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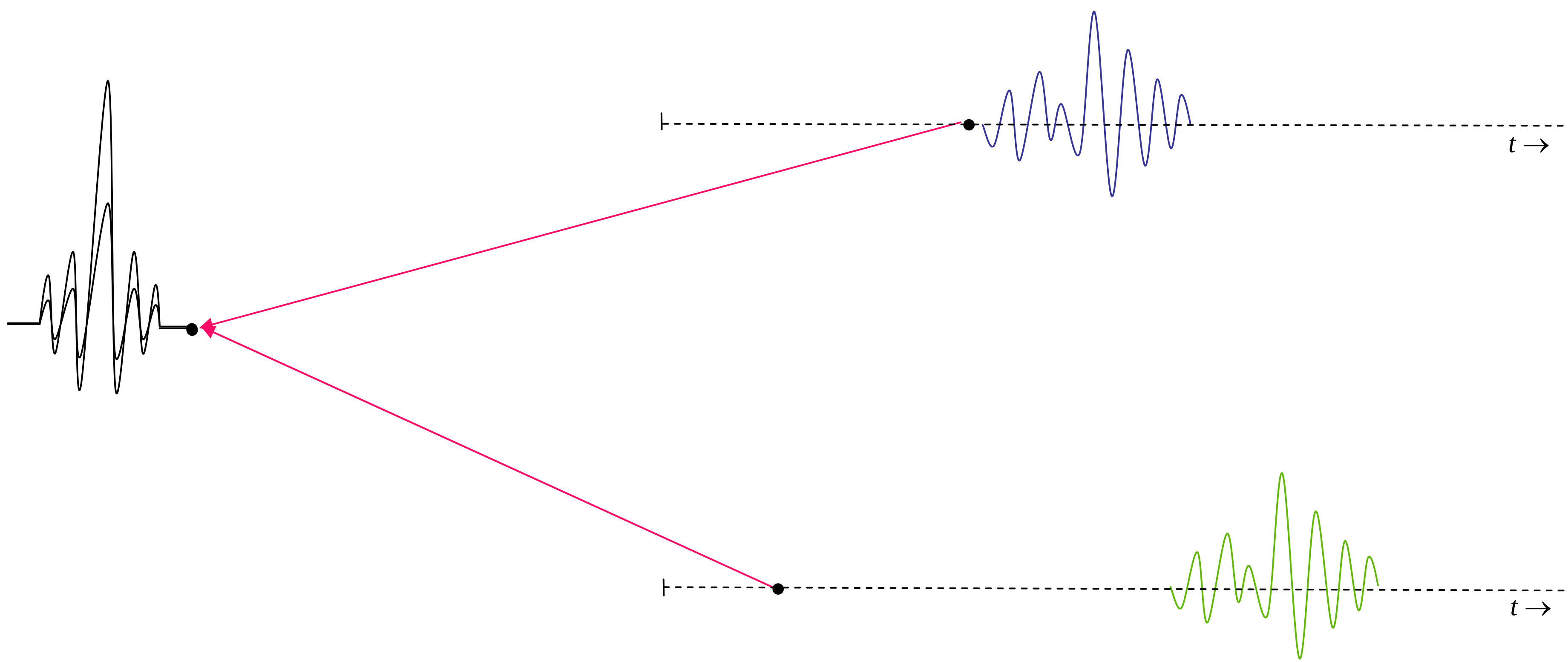

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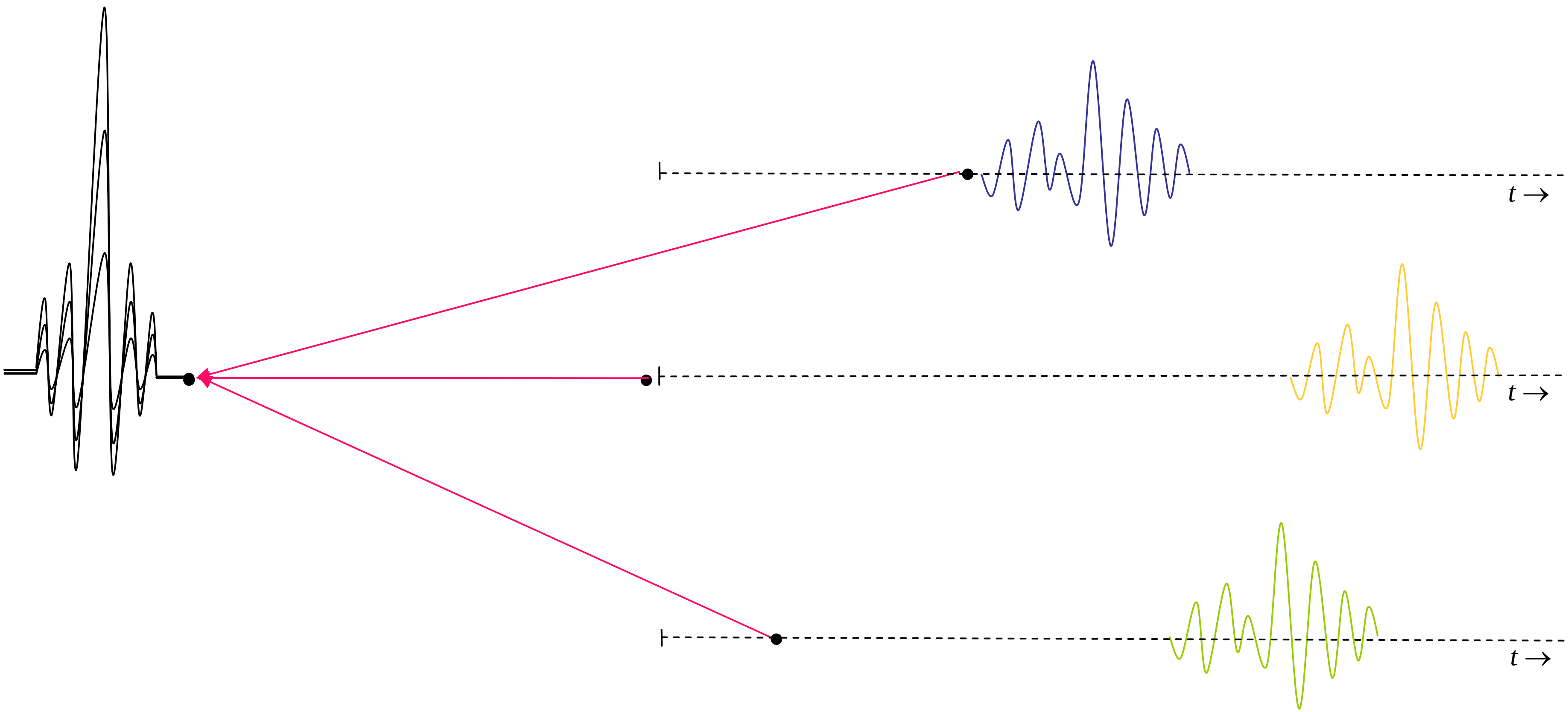


Properties – Optimality Lemma

- Let $h(t)$ represent the impulse response of the channel and let $\tilde{h}(t) = h(-t)$ represent the time reverse of the impulse response. Then, the instantaneous power output from the receiver node subject to an energy constraint at the transmitter is maximized by transmitting a multiple of the signal $\tilde{h}(t)$.
- The received signal $r(t)$ corresponding to the transmission of the signal $\tilde{h}(t)$ is given by the autocorrelation function of the channel impulse response; that is,

$$r(t) = \int_{-\infty}^{\infty} h(\tau)h(\tau + t)d\tau$$

Properties – Implications of lemma

- **TRC can be regarded as “matched signaling” for a channel rather than matched filtering.**
  - **Matching the signal to the channel and allowing the channel itself to function as the receiver filter rather than matching the receiver filter to the channel in order to maximize the output signal-to-noise ratio at a particular sampling time**

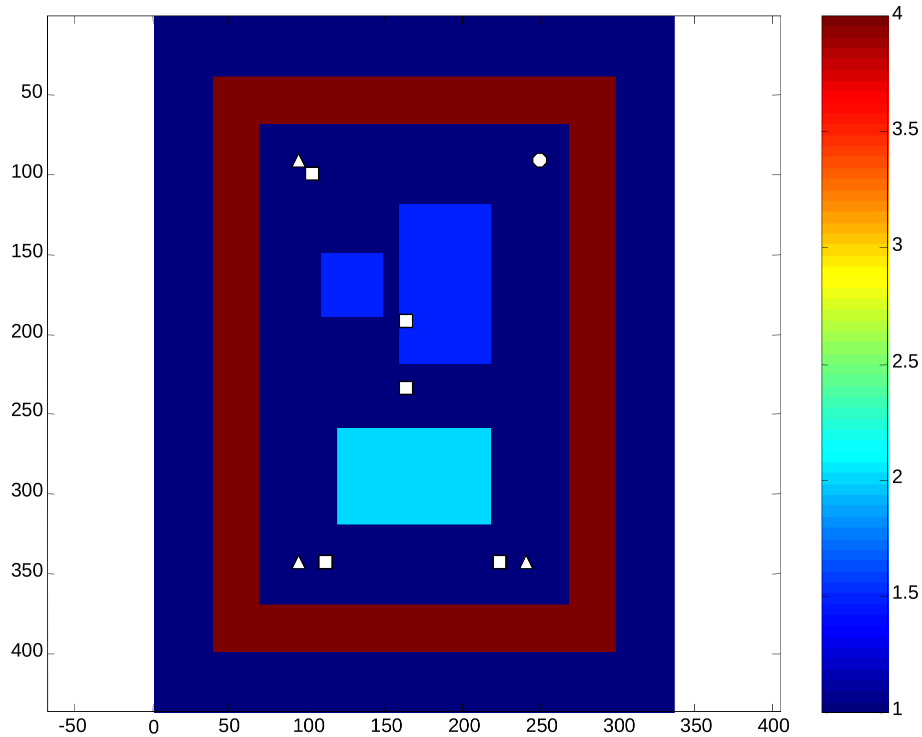
Properties – Implications of lemma

- **Cooperative TRC can be regarded as a generalization of *cooperative* or *distributed* beamforming that applies to both broadband and frequency-selective (i.e., dispersive) wireless channels where beamforming would ordinarily fail.**
  - **As the bandwidth of the transmitted training pulse decreases, TRC reduces exactly to beamforming. That is, the impulse response of the each channel reduces to a single complex-valued constant.**

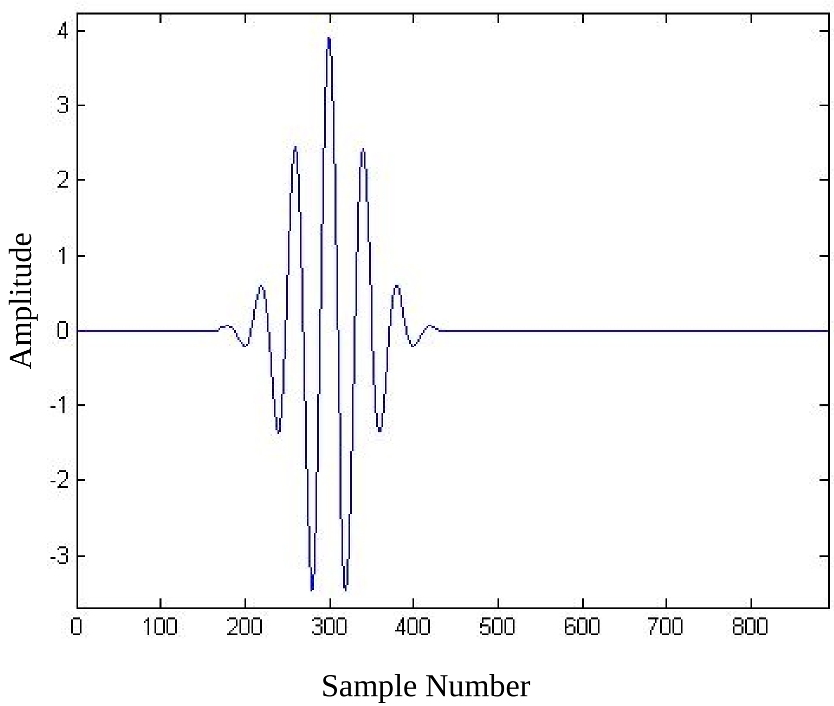
Properties – Implications of lemma

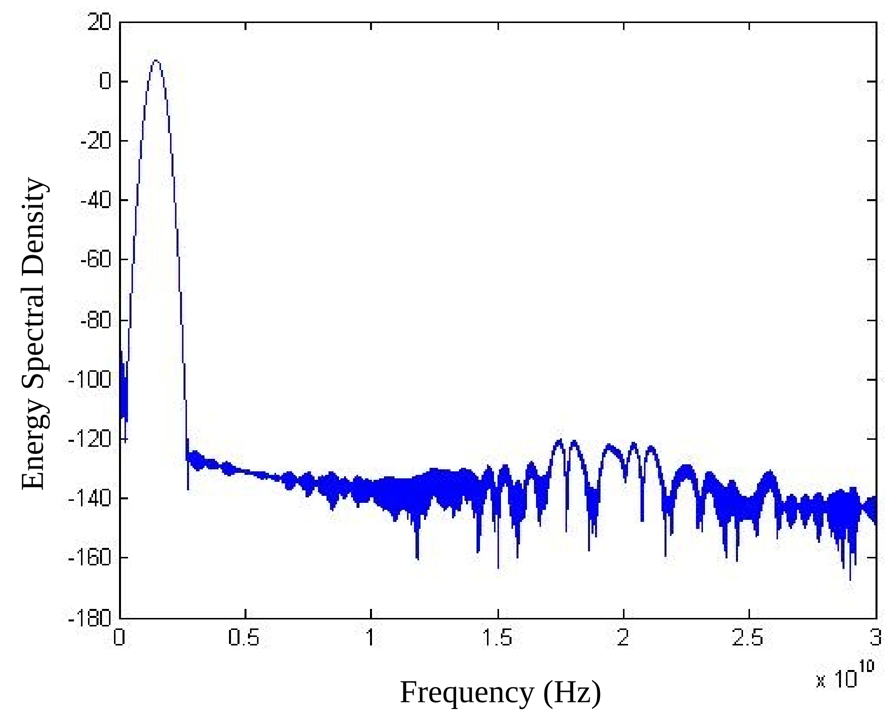
- **Output from a TR wireless channel tends to be concentrated in both space and time at the receiver.**
  - **The extent of the temporal and spatial focusing is determined by the spatial and temporal autocorrelation function of the channel.**
  - **Lemma does *not* imply that TRC is the optimal method of focusing energy in either time or space. Optimal method of accomplishing such focusing, without regard to the energy required to do so, is pre-equalization of the channel at the transmitter.**

Simulated Performance Results – Environment

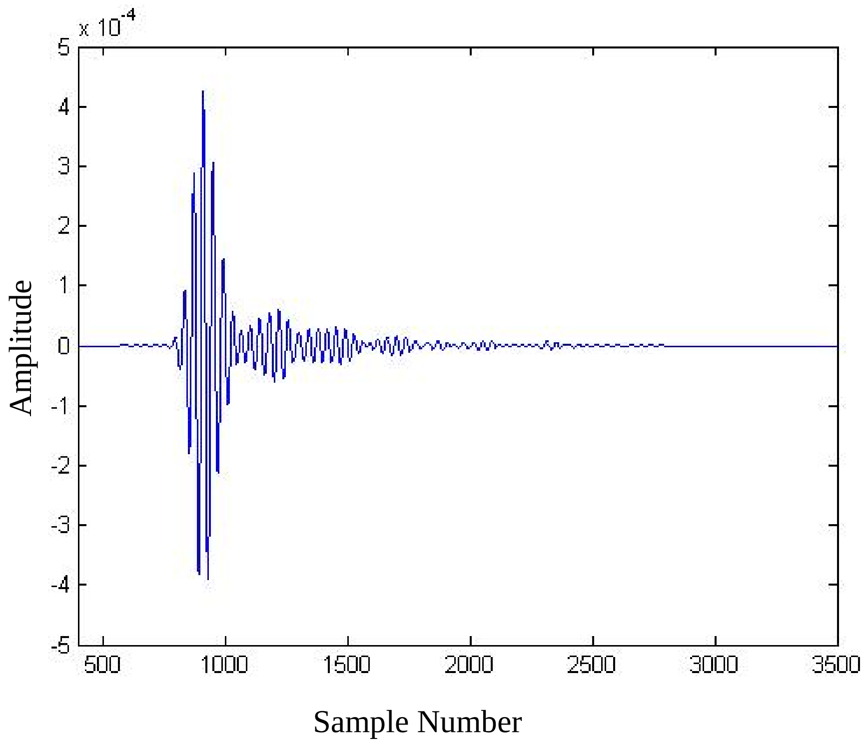


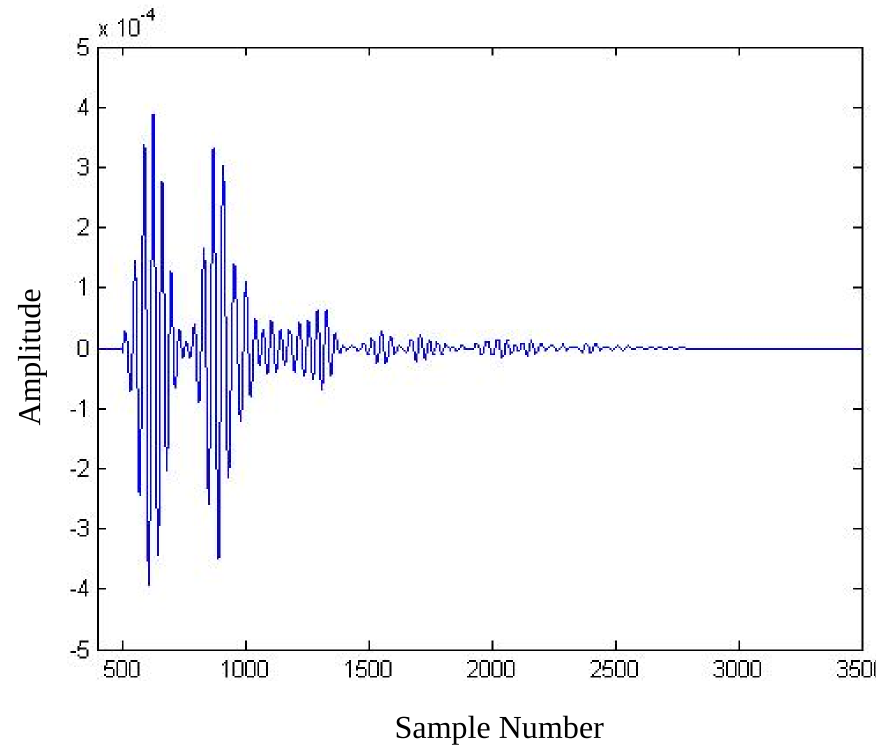
Simulation Results – Transmitted Waveform



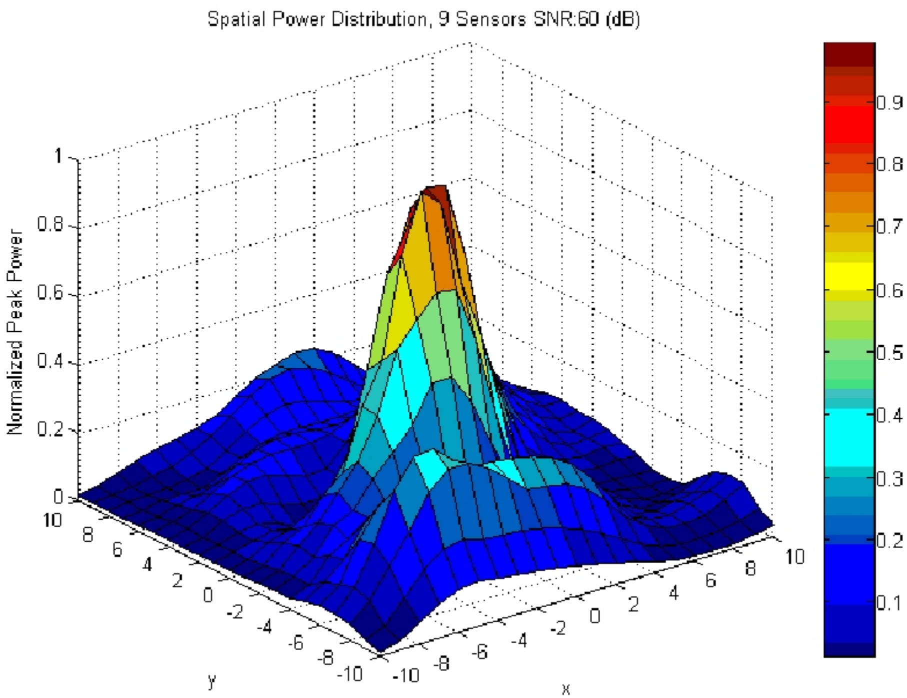


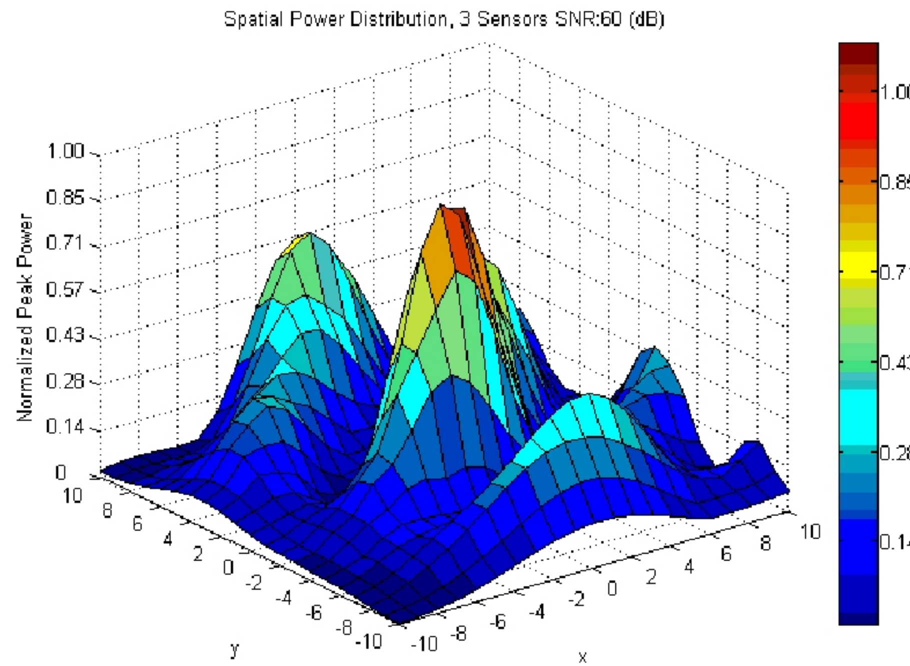
Simulation Results – Example Received Waveforms



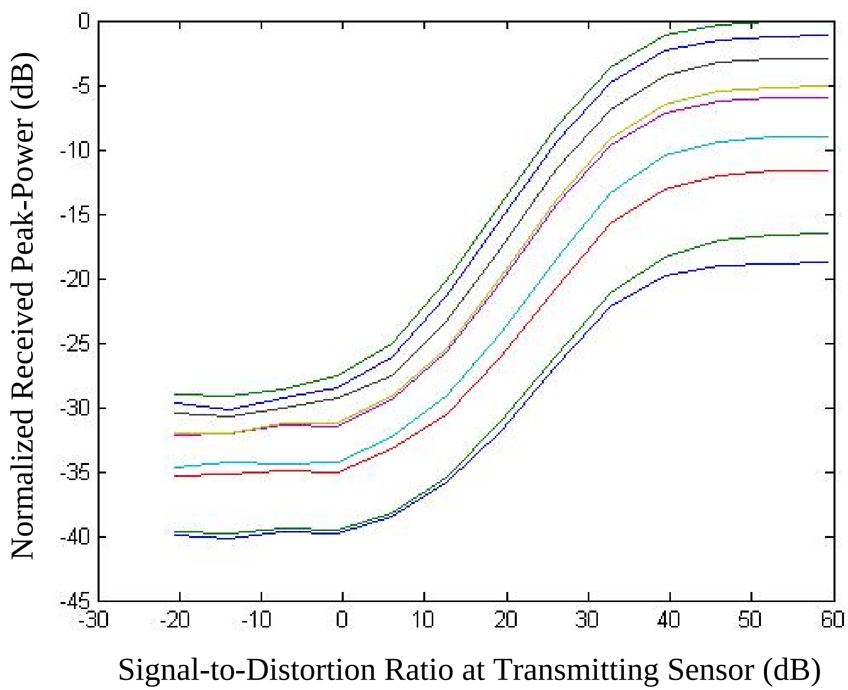


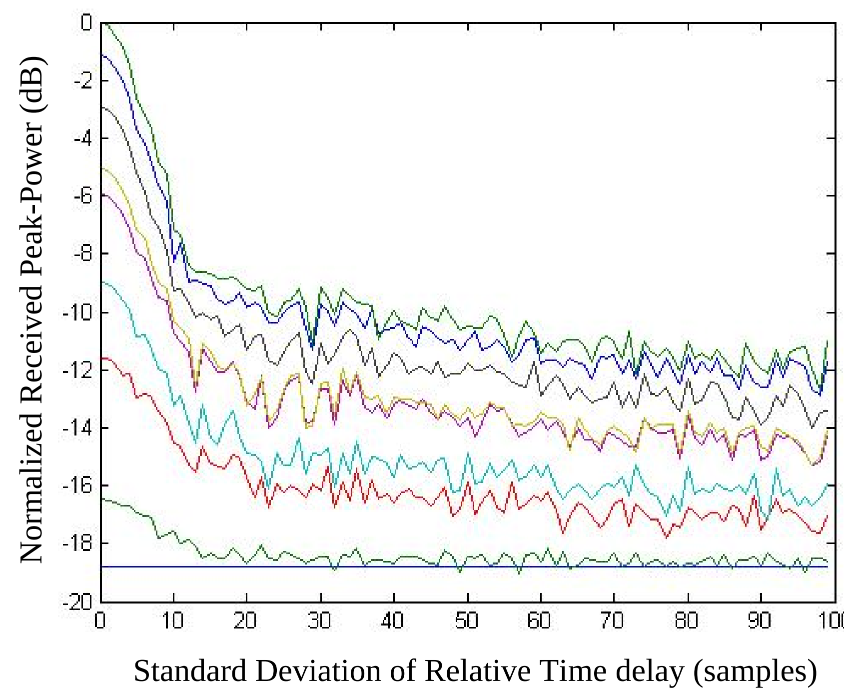
Simulation Results – Spatial Power Distribution



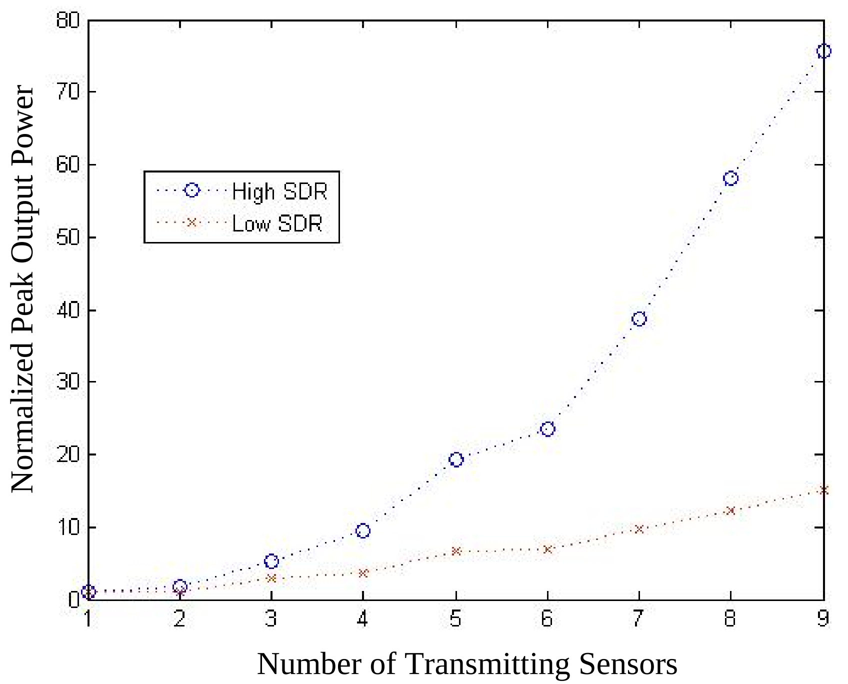


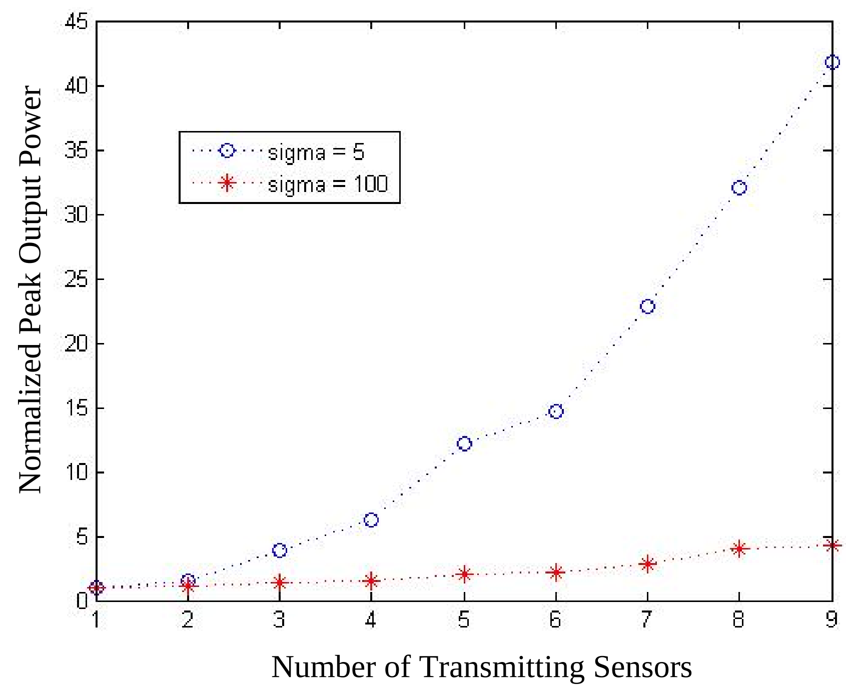
Simulation Results – Pulse Estimation and Timing Errors



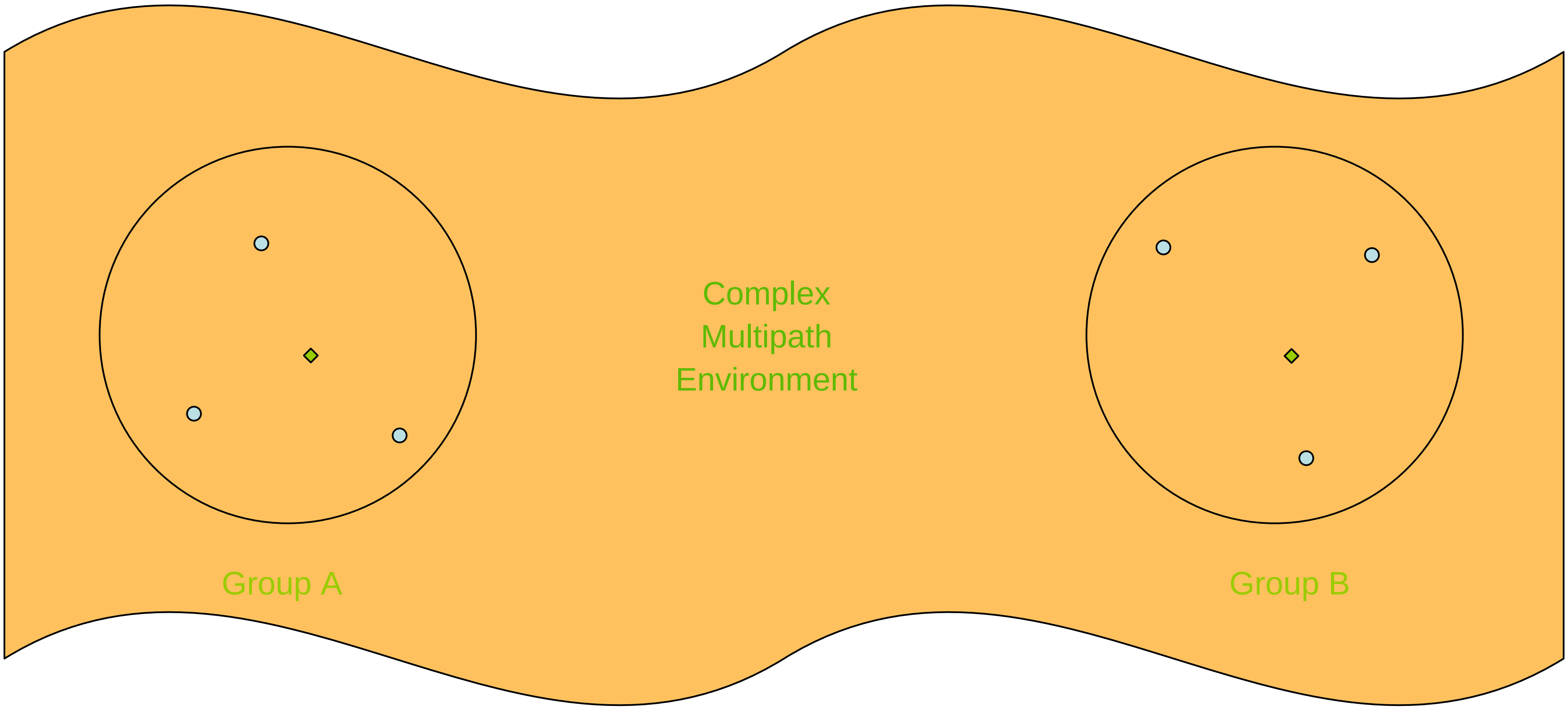


Simulation Results – Growth Rate of Peak Power



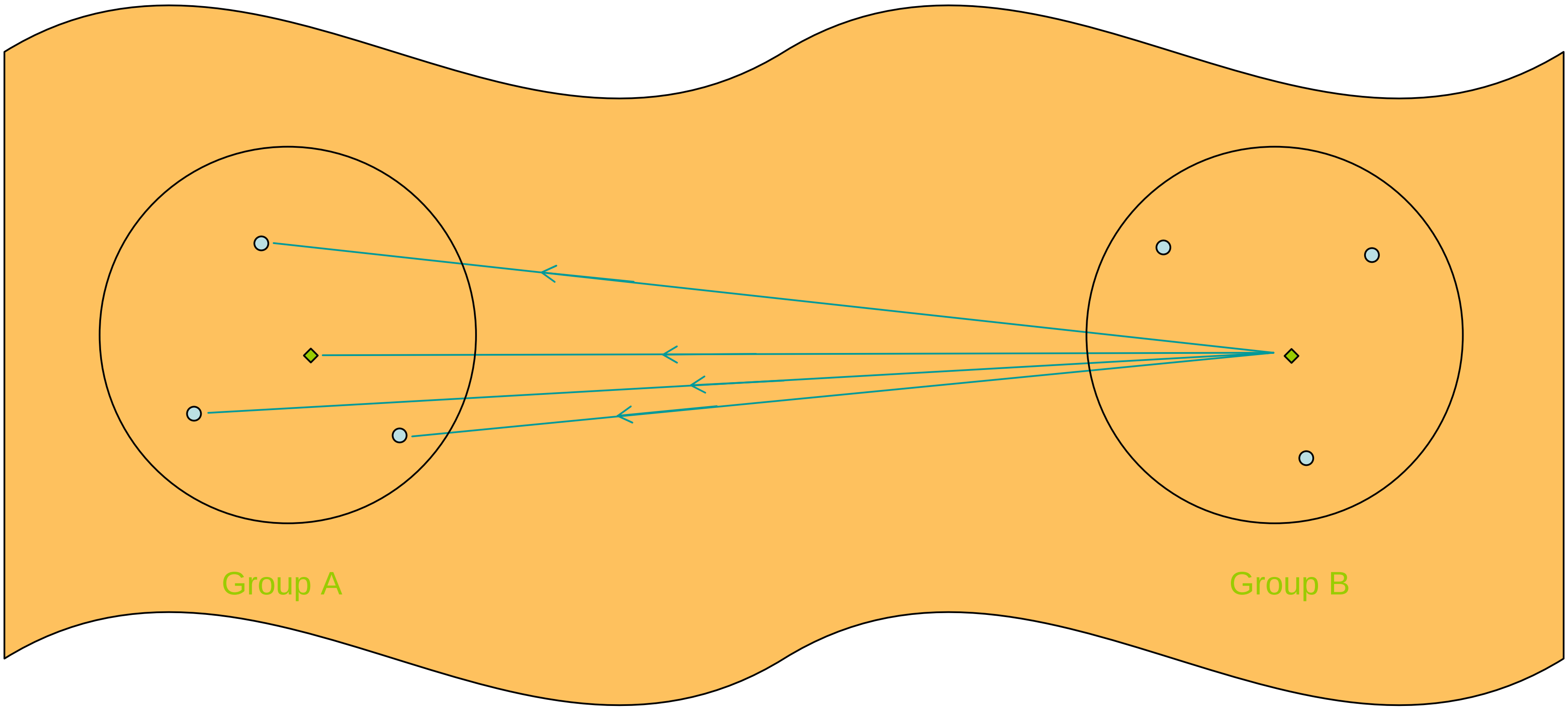


Applications – Cluster-to-Cluster Communication



- Receiver Sensors
- Cooperating Sensors

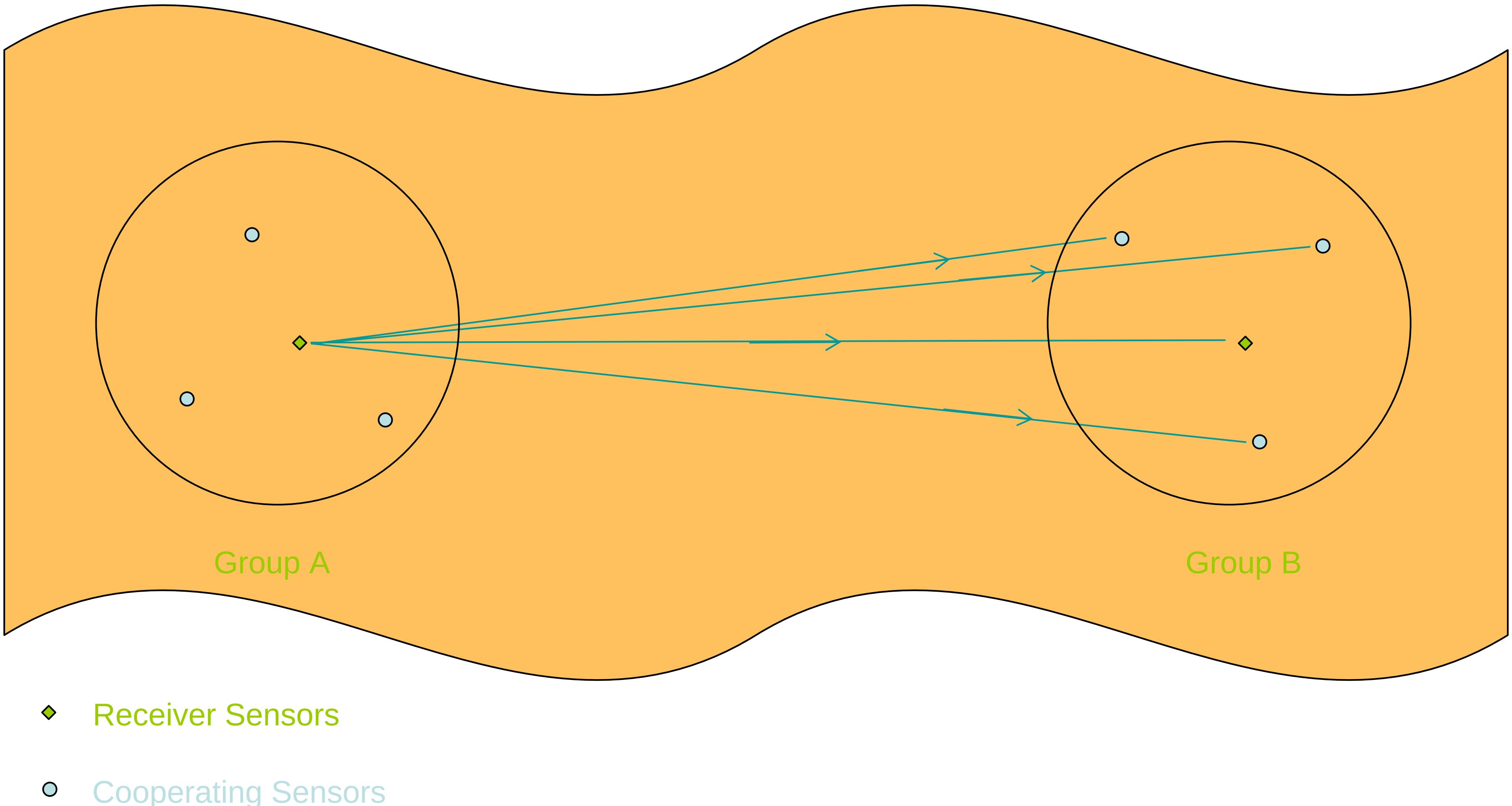
Cluster-to-Cluster Comm – Training for A to B



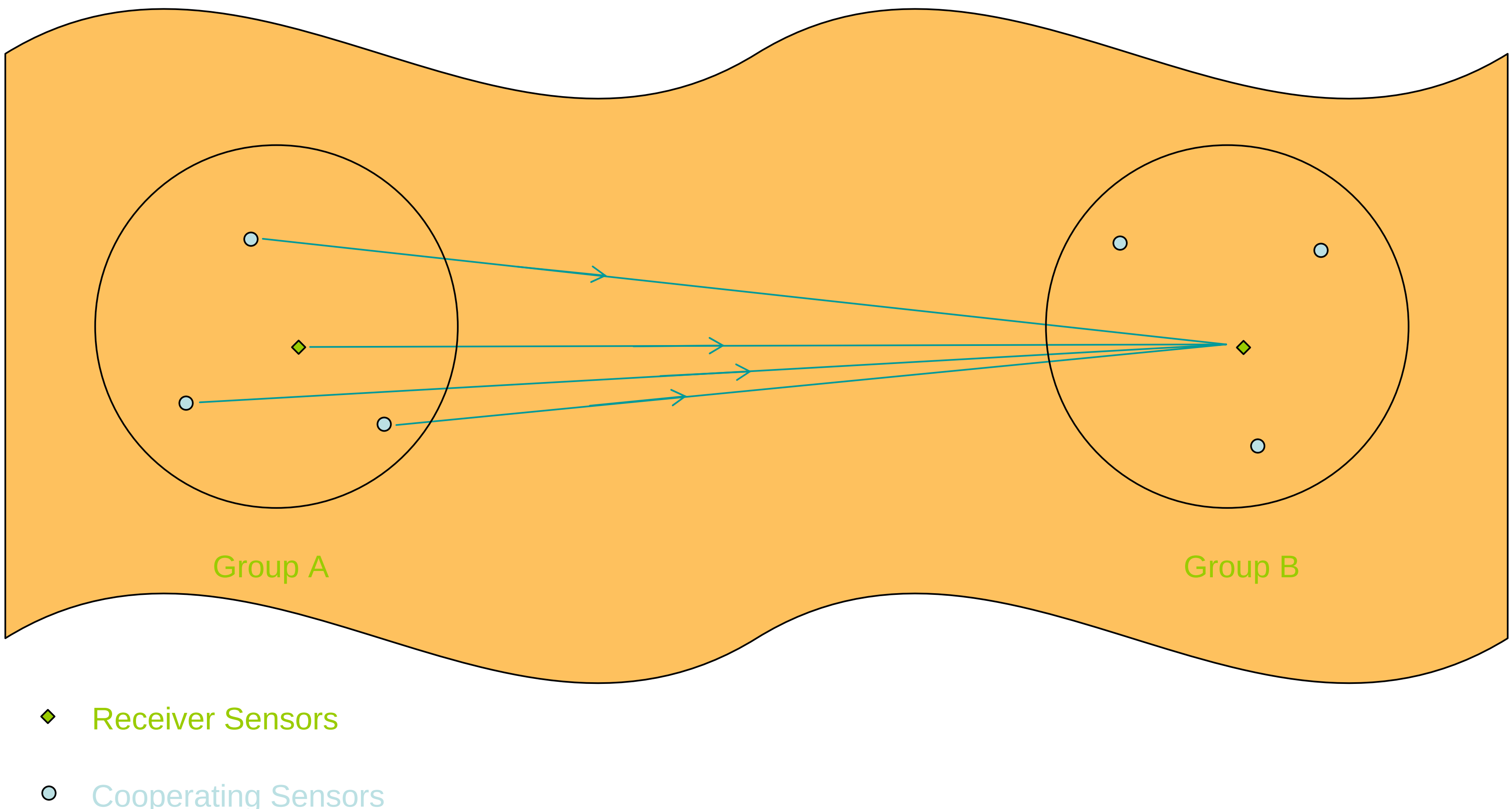
Receiver Sensors

Cooperating Sensors

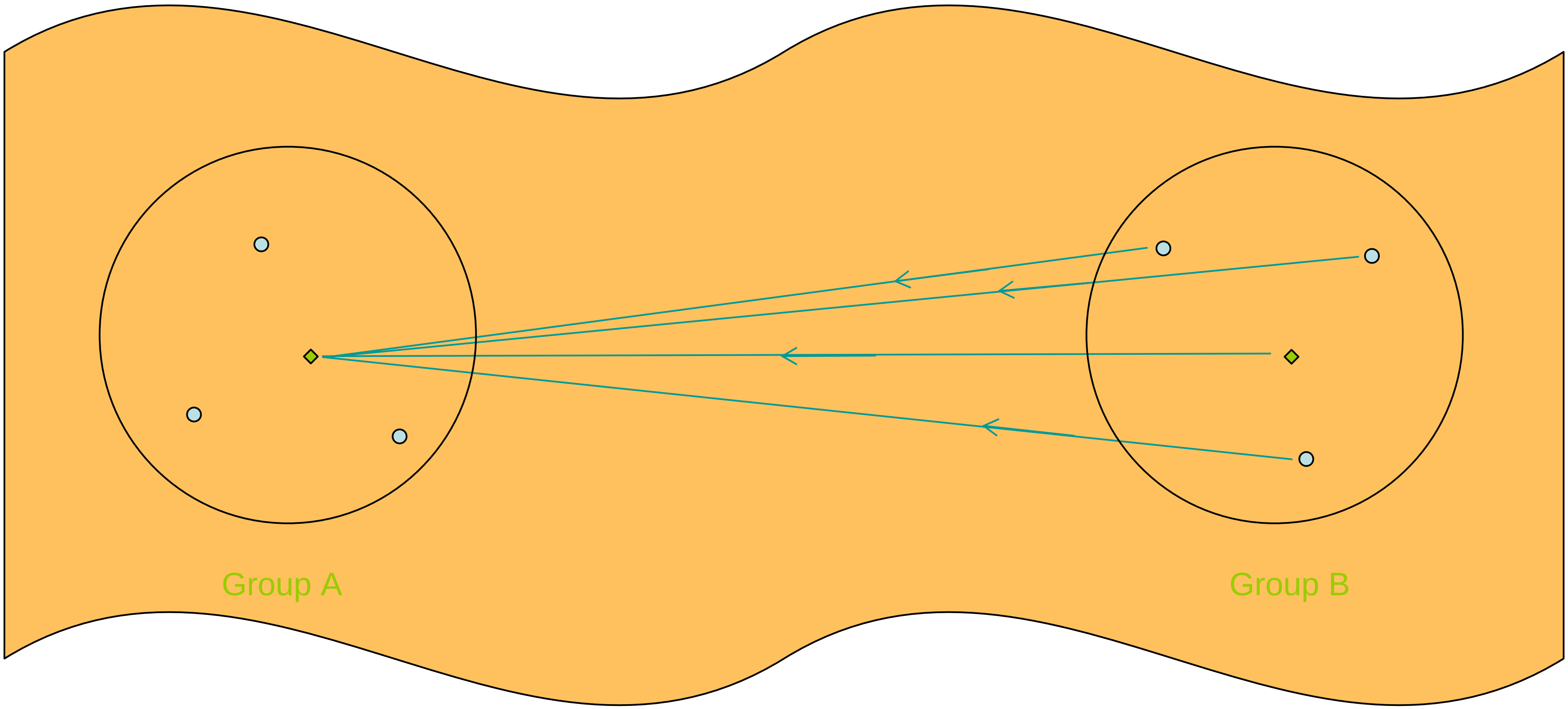
Cluster-to-Cluster – Training for B to A



Cluster-to-Cluster Comm – Transmission from A to B



Cluster-to-Cluster Comm – Transmission from B to A



- Receiver Sensors
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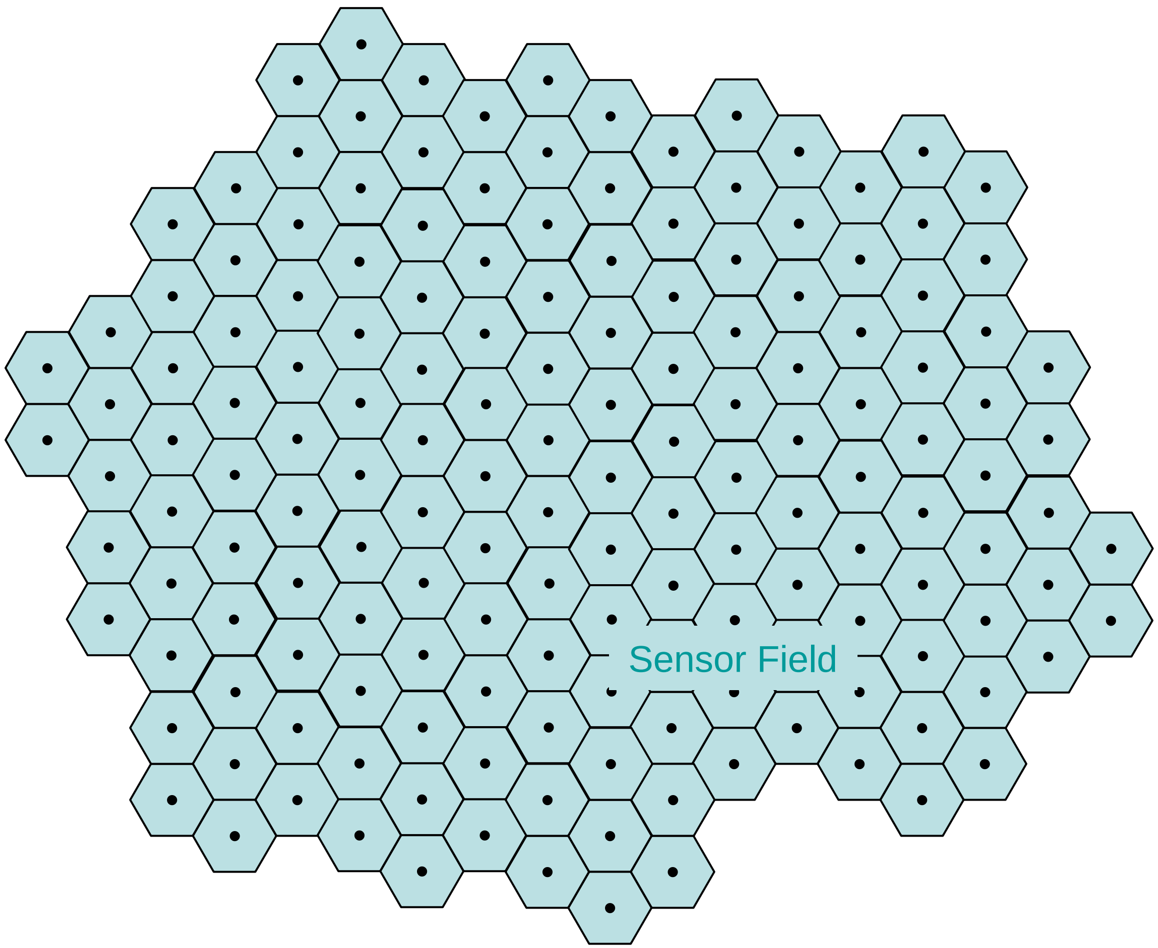
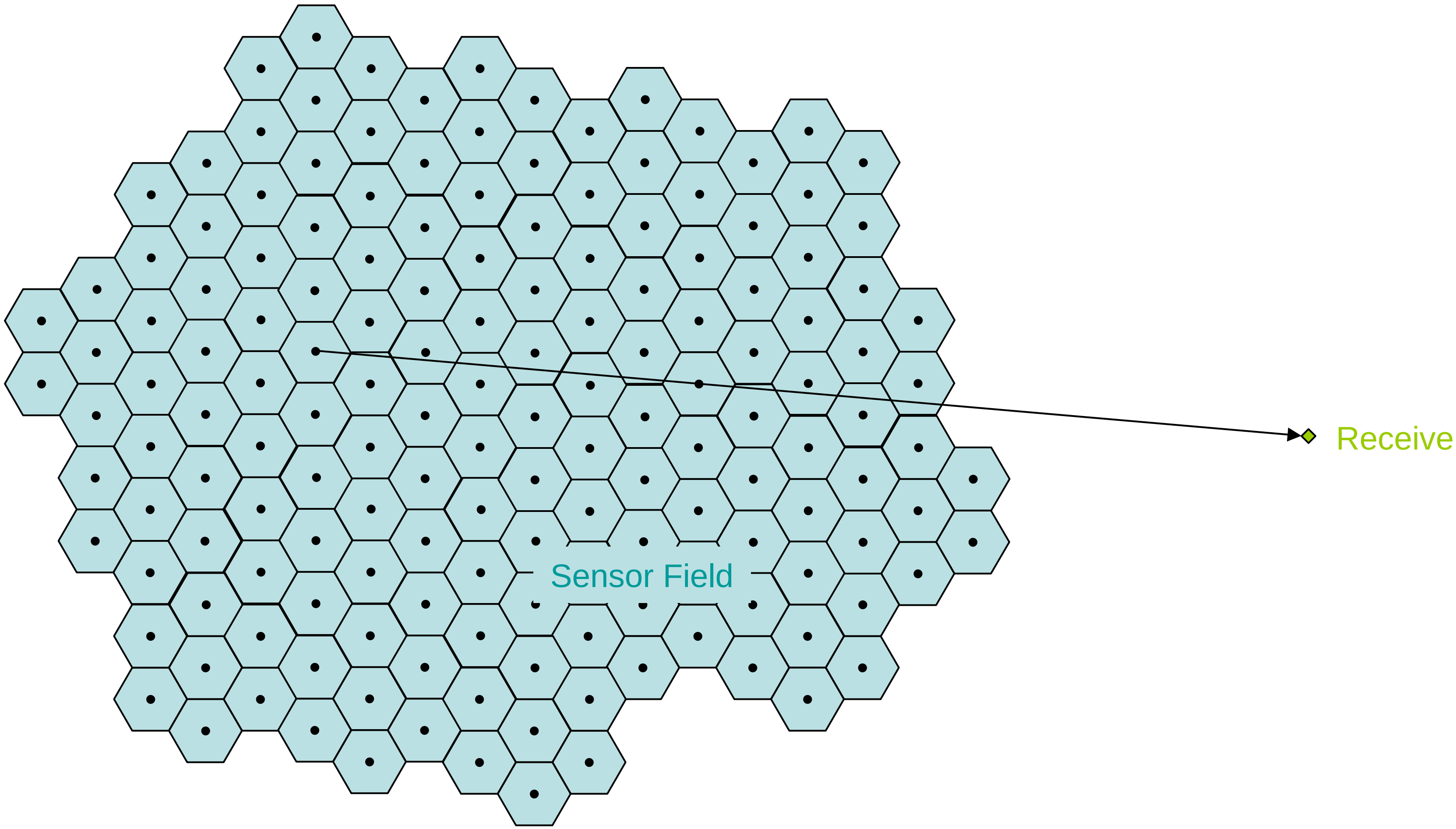
Applications – Adaptive Sensor Interrogation



- Receiver

Adaptive Sensor Interrogation – Low-Rate, High-Resolution



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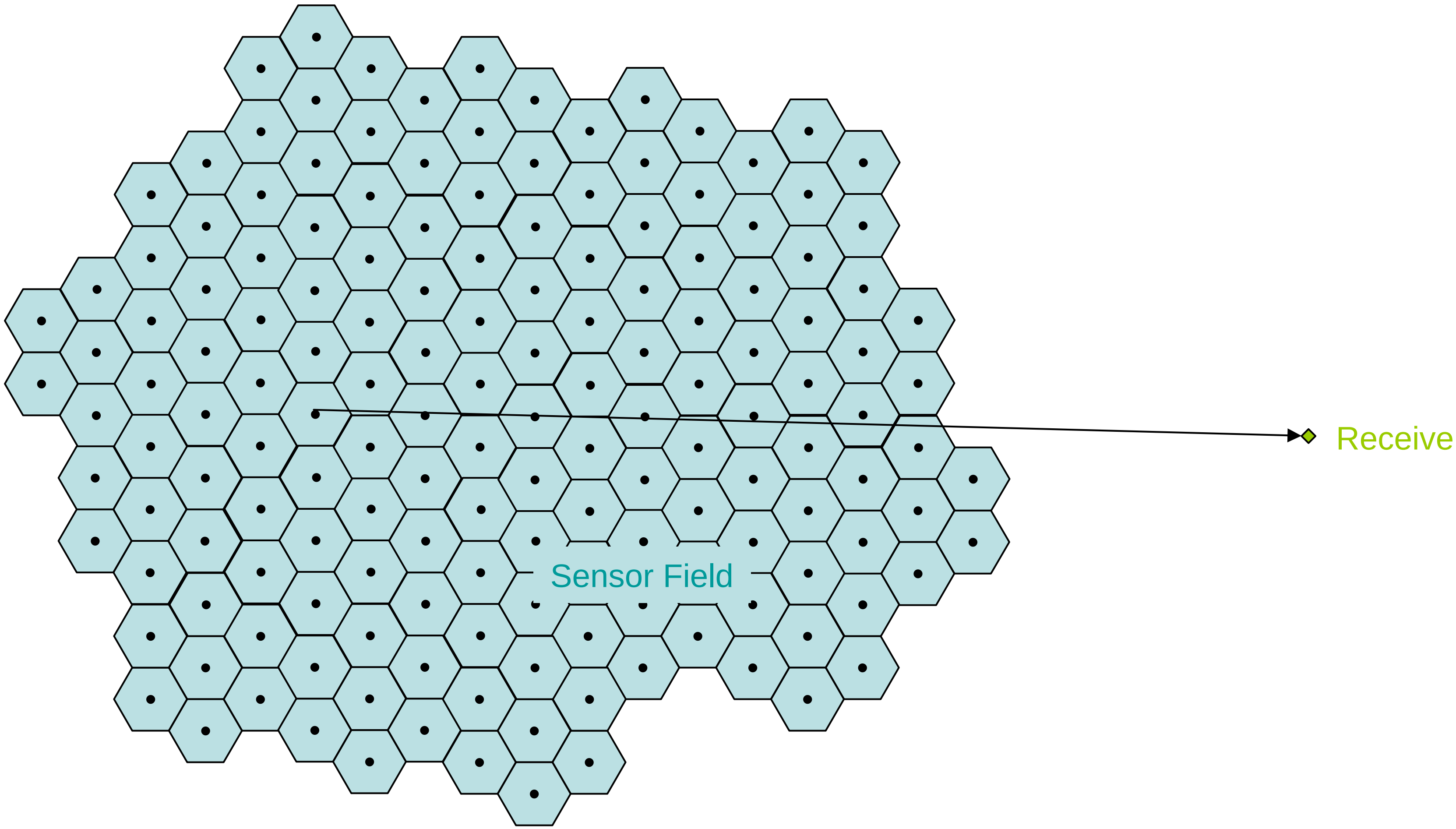
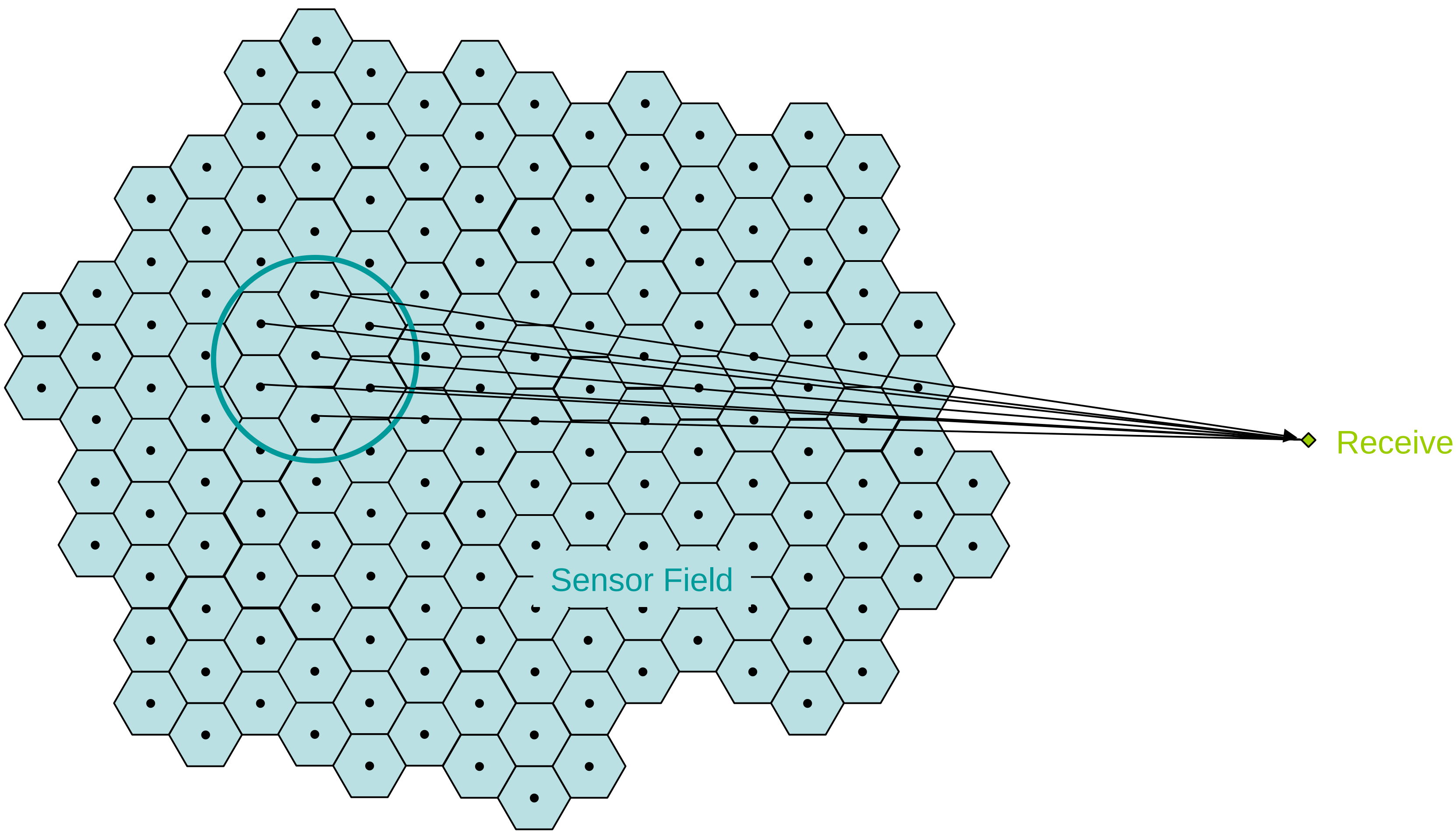
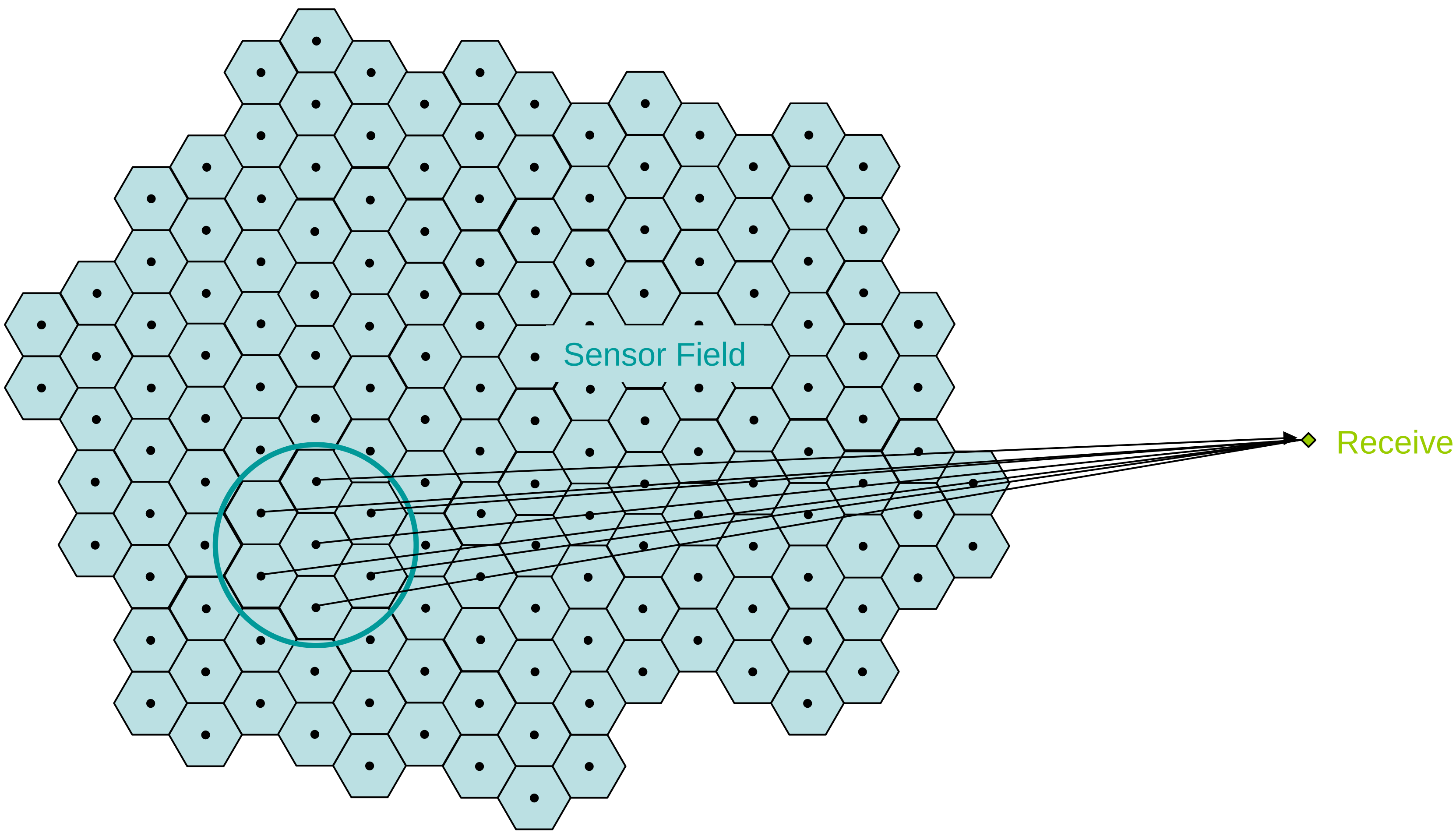


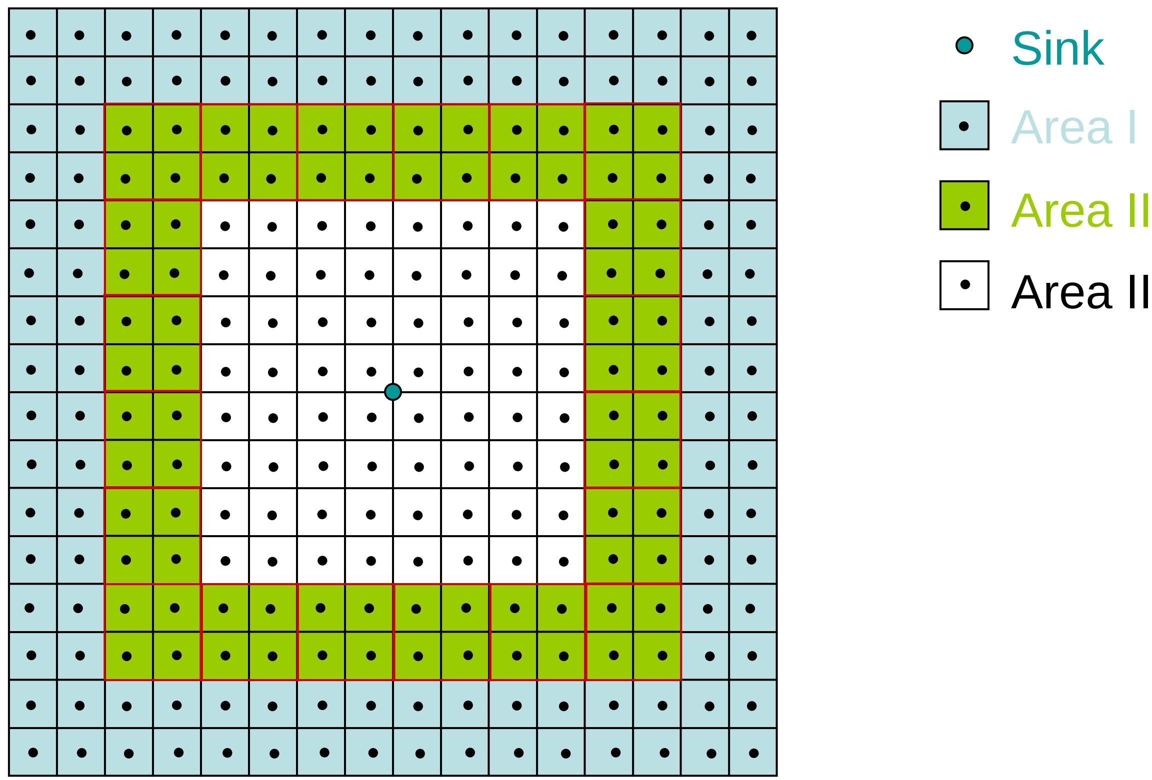
Adaptive Sensor Interrogation – High-Rate, Low-Resolution



Adaptive Sensor Interrogation – High-Rate, Low-Resolution

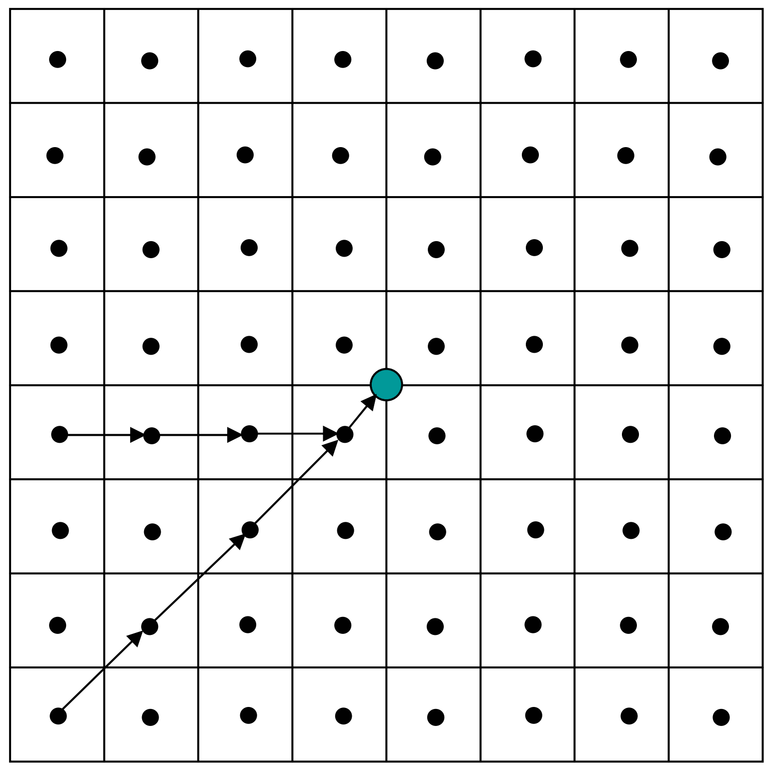


Applications – Data Aggregation in WSNs



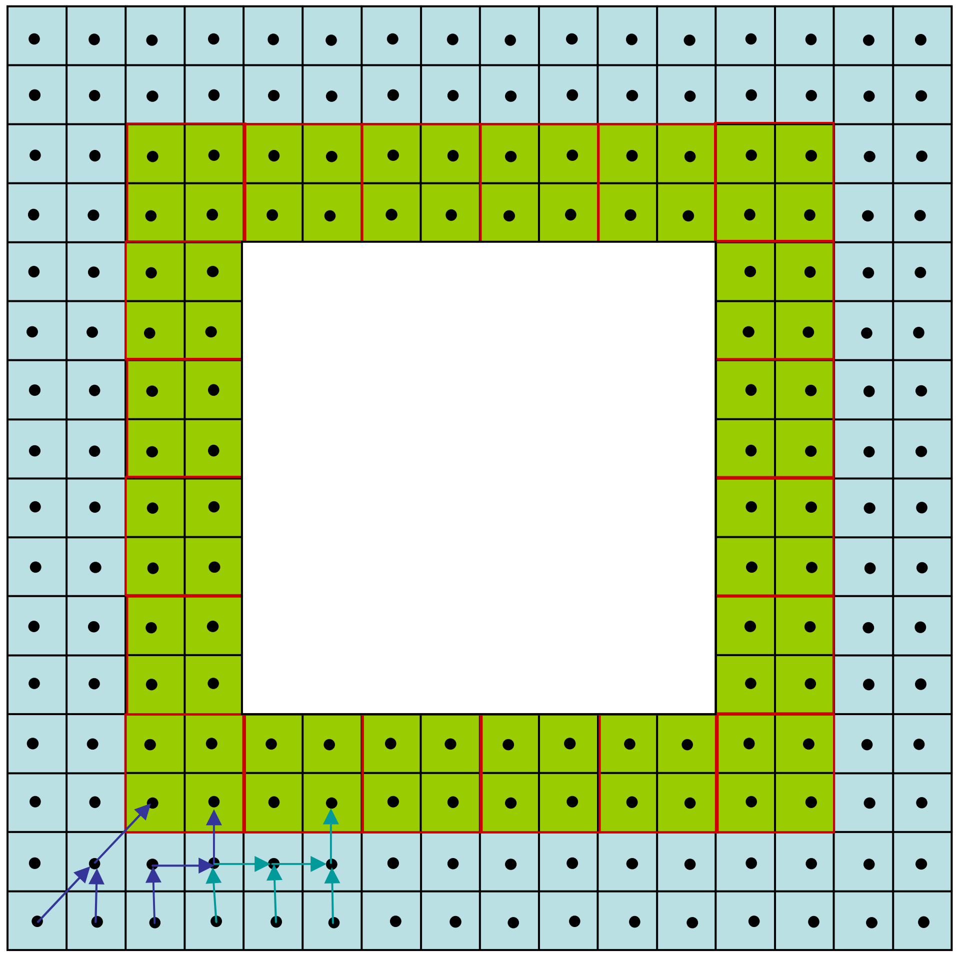
Data Aggregation in WSNs – Network Protocol

- **Area III – Multihop to Sink**



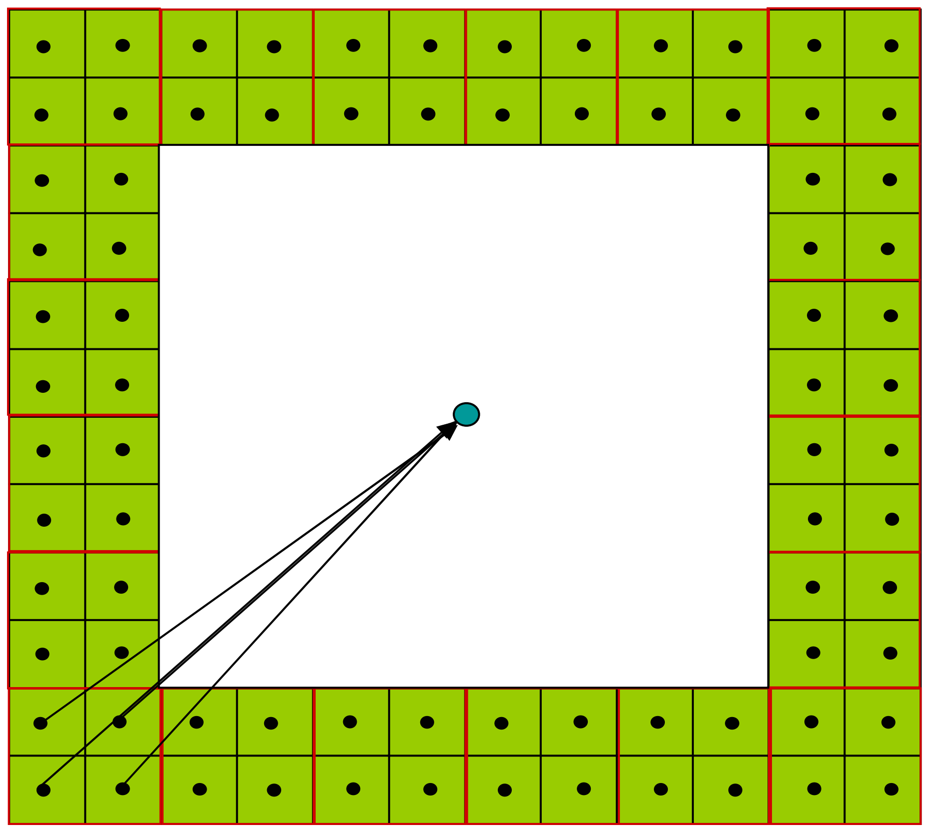
Data Aggregation in WSNs – Network Protocol

- **Area I - Multihop on Trees to Area II**



Data Aggregation in WSNs – Network Protocol

- **Area II - Cooperative TRC to Sink**



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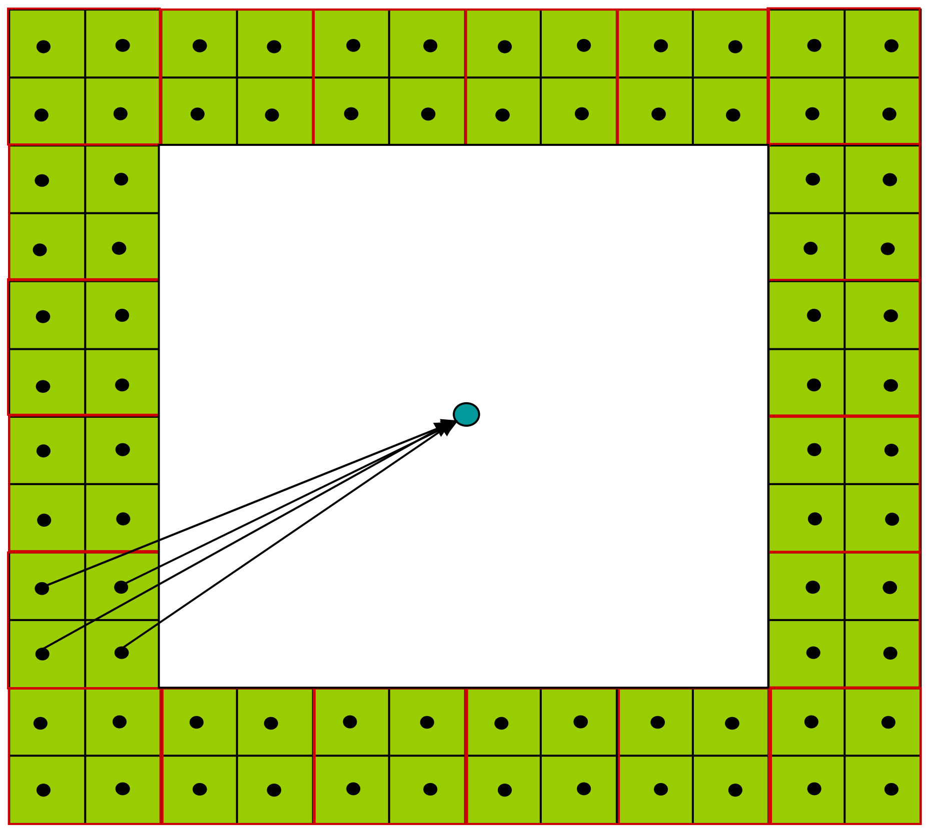

Optimal Data Aggregation in WSNs

- **Question: What is the asymptotically achievable data aggregation rate at the sink in a wireless sensor network of *n* nodes in a fading environment?**

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  - **Order optimal throughput can be achieved using cooperative TRC and the hierarchical network protocol described previously.**
  - **Data aggregation using multihop relay is suboptimal except for $\alpha > 4$.**
  - **TRC can improve network life time by an order of magnitude for low-duty cycle operations.**

Conclusions

- **TRC provides an efficient way to communicate in a complex, broadband environment.**
- **Accurate channel estimation and precise synchronization are critical.**
- **To unleash the power of TRC in a network setting, cross-layer design of routing, scheduling and communication protocols are required – cooperation, cooperation, cooperation!**