Effect of Network Architecture on Population Synchronization in A Scale-Free Network of Bursting Neurons

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Introduction

- **Burstings with the Slow and Fast Time Scales**
  Bursting: Neuronal activity alternates, on a slow timescale, between a silent phase and an active (bursting) phase of fast repetitive spikings

- **Synchronization of Bursting Neurons**
  Two Different Synchronization Patterns Due to the Slow (**Burst Synchronization**: Synchronization between the bursting onset or offset times) and Fast (**Spike Synchronization**: Synchronization between intraburst spikes) Time Scales of Bursting Activity

- **Complex Topology of Real Brain**
  - Connection architecture of the real brain reveals complex topology such as small-worldness and scale-freeness which are neither regular nor random.
  - Our neuronal model: Scale-Free Network (SFN)

- **Purpose of Our Study**
  Investigation of Effect of Network Architecture on Burst and Spike Synchronization in A Directed SFN

Directed SFN of Inhibitory Bursting Neurons

- **Directed SFN**

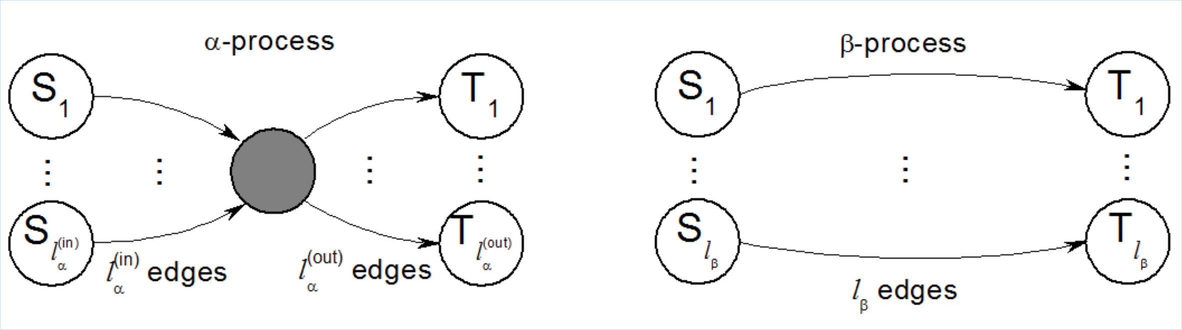
  Directed Variant of the Barabási-Albert (BA) SFN model

  α-process: Directed version of BA model

  Growth and preferential directed attachment

  β-process: Symmetric preferential attachment

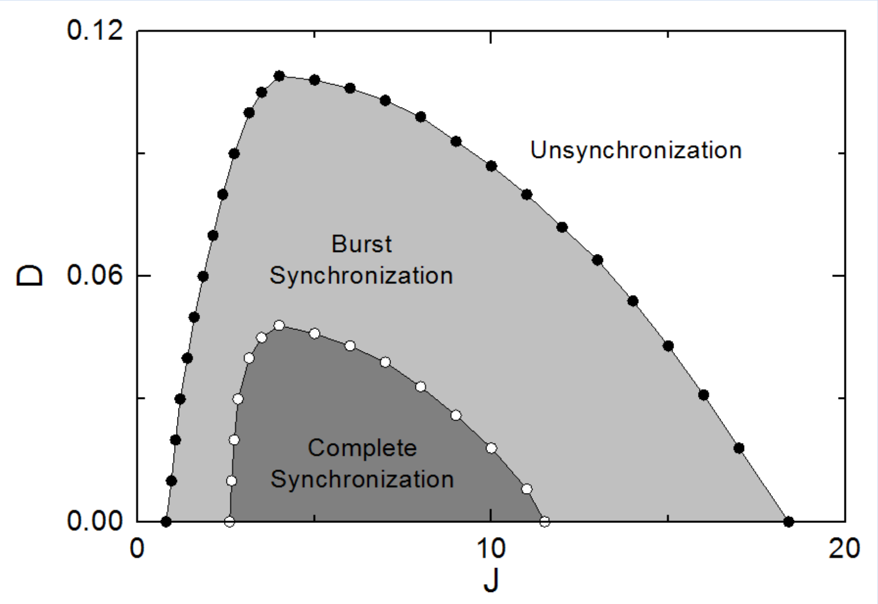
  without addition of new nodes (No growth)



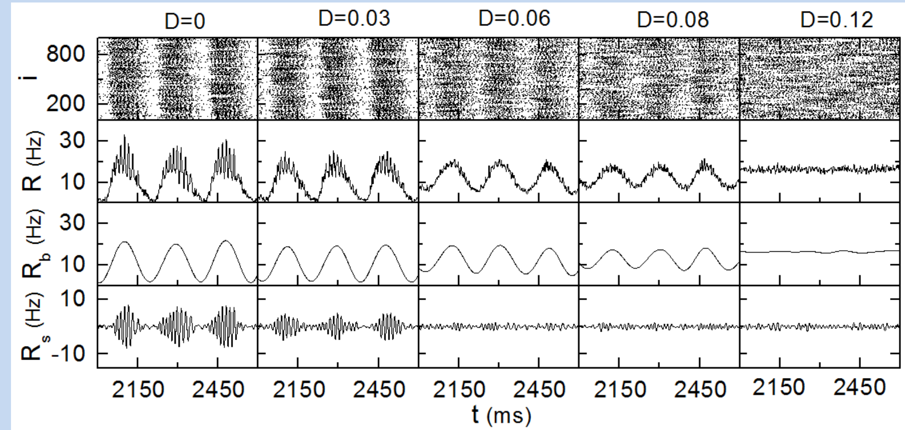
- **Directed SFN of Inhibitory Suprathreshold Bursting Hindmarsh-Rose Neuron**

Burst and Complete Synchronization in Directed SFN for I_{DC}=1.4

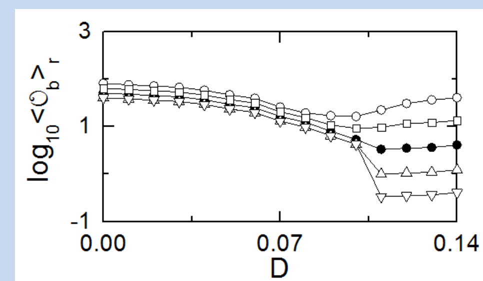
- **State Diagram in the J-D Plane**
  - Burst Synchronization
  - Complete Synchronization
    (compose of both burst and spike synchronization)

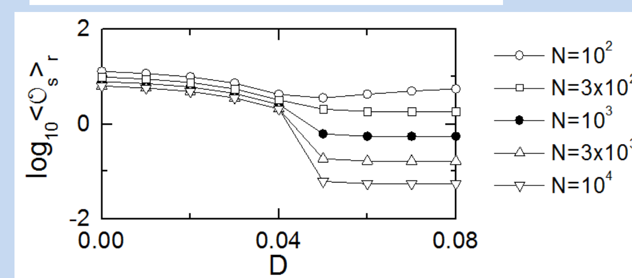


Burst and Complete Synchronization for J=4



- **Characterization of Burst and Spike Synchronization via Separation of Slow (Bursting) and Fast (Spiking) Timescales**
  - Raster Plot of Neural Spikes:
    Population synchronization may be well visiualized. Obtained in experiments
  - Instantaneous Population Firing Rate (IPFR) R:
    Describing the population behaviors
  - Separation of the Slow and Fast Timescales of Bursting Activity via Frequency Filtering
    Instantaneous Population Bursting Rate (IPBR) R_b: Describing the slow bursting behavior
    Instantaneous Population Spiking Rate (IPBS) R_s: Describing the fast spiking behavior





- **Determination for Bursting and Spiking Threshold via Thermodynamics Bursting and Spiking Order Parameters**

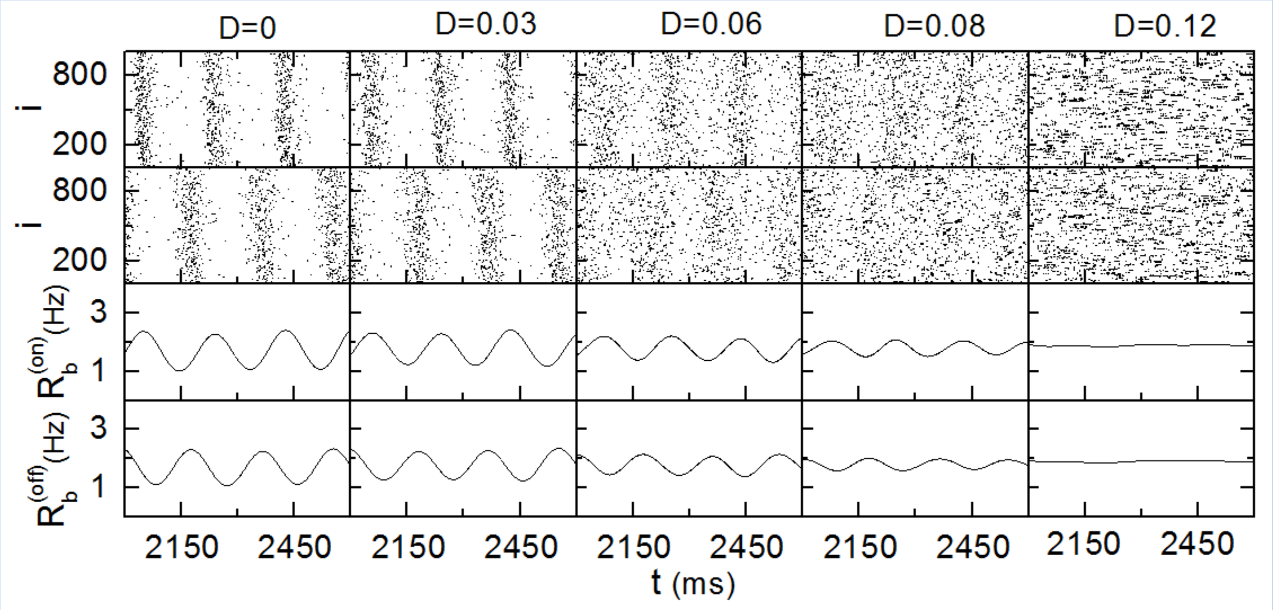
  Thermodynamic Bursting ($\mathcal{O}_b$) and Spiking ($\mathcal{O}_s$) Order Parameters: Mean square deviation of R_b and R_s

  For Burst (Intraburst Spike) Synchronization:
  $N \to \infty$, $\mathcal{O}_b$ ($\mathcal{O}_s$) $\to$ non-zero values.
  For Burst (Intraburst Spike) Unsynchronization:
  $N \to \infty$, $\mathcal{O}_b$ ($\mathcal{O}_s$) $\to$ 0.

Characterization of Burst Synchronization Based on Bursting Onset and Offset Times

- **IPBRs for Active Phase (Bursting) Onset and Offset Times**
  - Raster plots of active phase onset and offset times
    More direct visualization of bursting behavior.

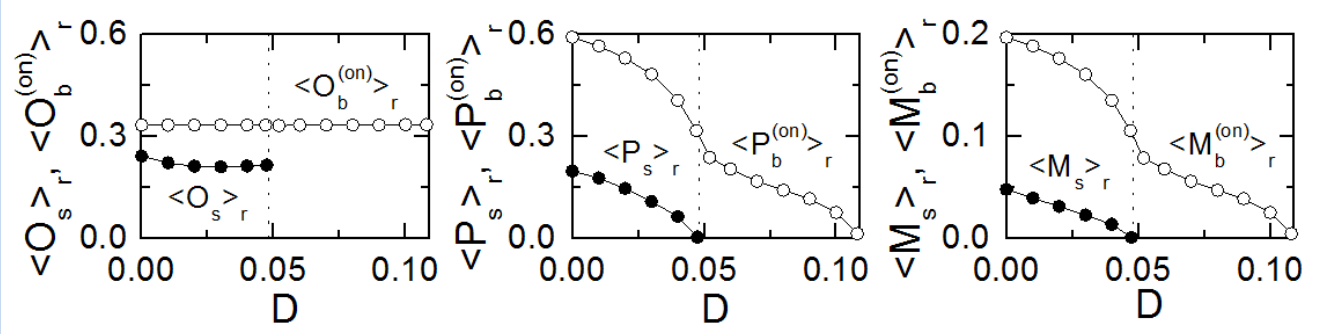
  → IPBRs for active phase onset and offset times



Measurement of Degree of Bursting and Intraburst Spike Synchronization

- **Statistical-Mechanical Bursting and Spiking Measures**
  - Occupation Degree: representing the density of stripe in the raster plot
  - Pacing Degree: representing the smearing of stripe in the raster plot
    (average contribution of all microscopic bursting and spiking in the stripe)
  - Statistical-Mechanical Bursting and Spiking Measure:
    Joint Effect of Occupation and Pacing Degrees

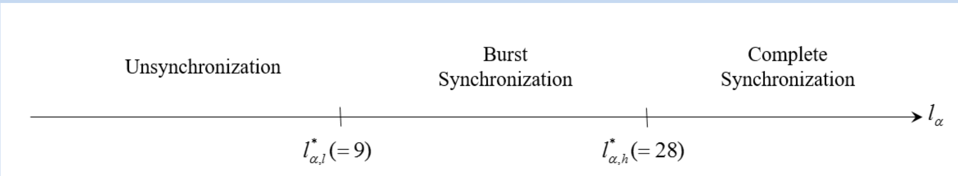
As D is increased, the pacing degree for bursting and spiking decreases.

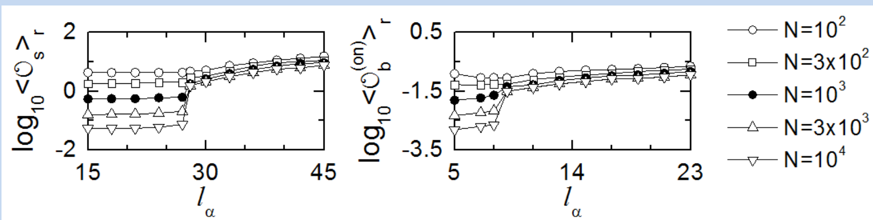


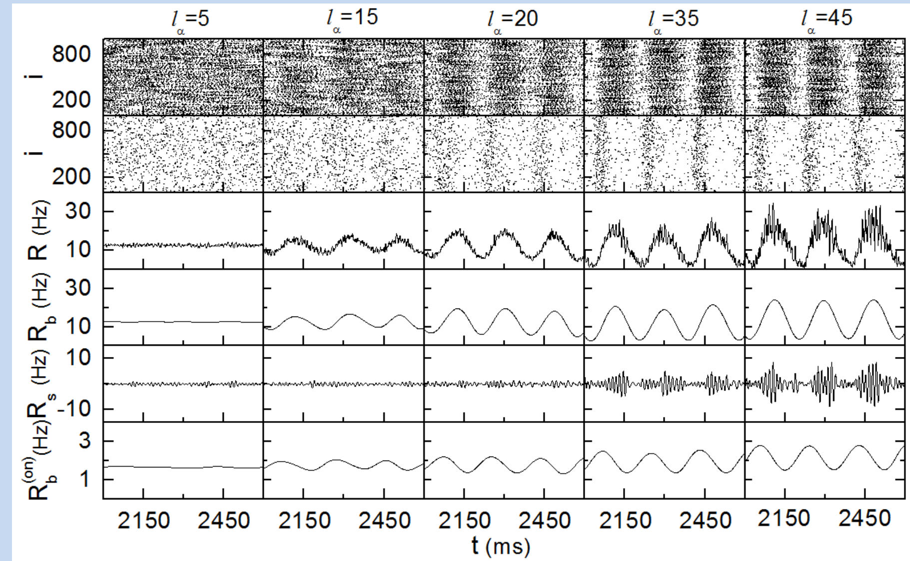
Effect of l_α on Burst and Spike Synchronization

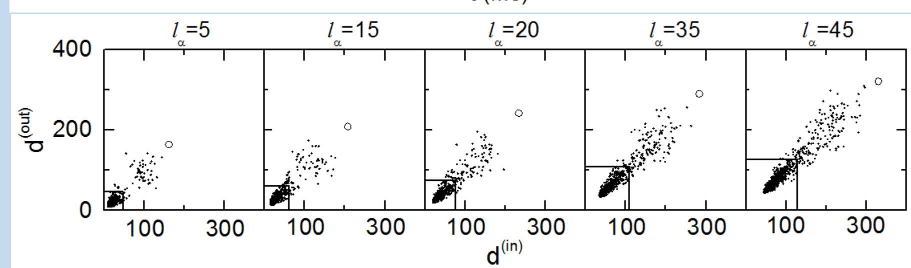
$$(I_{DC} = 1.4,\ J = 4,\ D = 0.06,\ \&\ l_\alpha^{(in)} = l_\alpha^{(out)} \equiv l_\alpha)$$

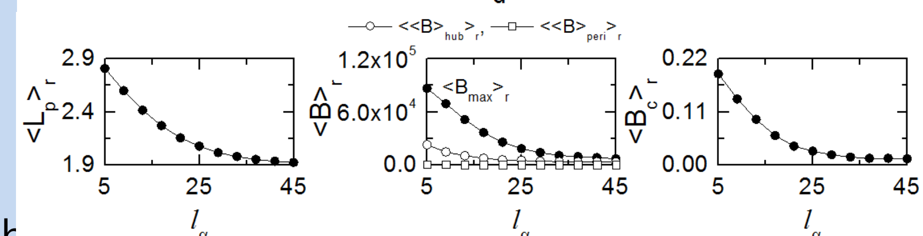
- **Burst and Complete Synchronization**











- **Effect of l_α on the Network Topology**
  - Average path length L_p: Typical separation between two nodes in the network
  - Betweenness centrality B_i: Potentiality in controlling communication between other nodes
  - Betweenness centralization B_c: Degree to with B_{max} of the head hub exceeds the B_i of all other nodes

As l_α is increased, L_p decreases.
B_{max} of head hub is much more reduced than the average centralities of the secondary hubs and the peripheral nodes. → B_c decreases.
⇒ Efficiency of communication between nodes becomes better, which may lead to increase in the degree of burst and spike synchronization.

Effect of l_α on Burst and Spike Synchronization

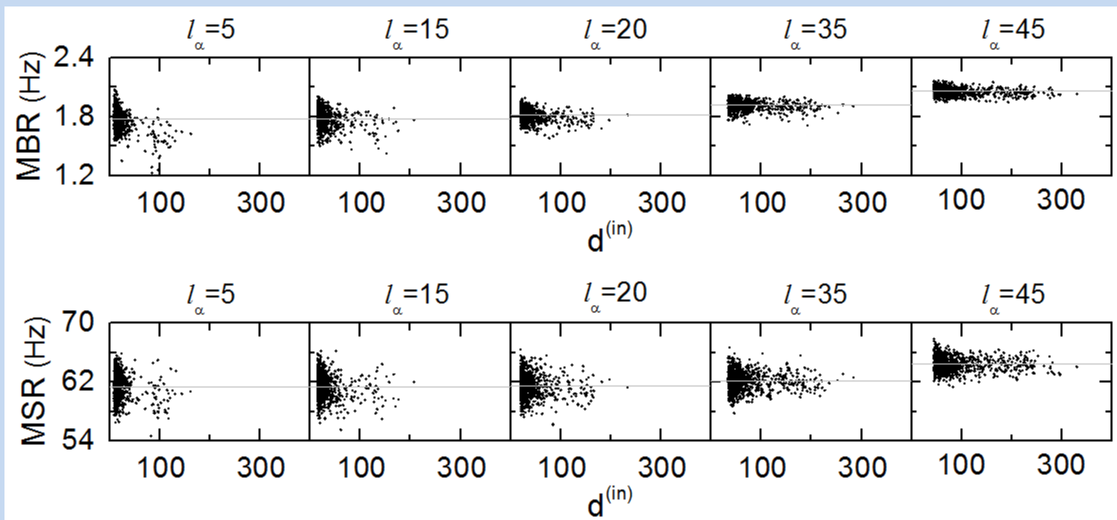
- **Effect of l_α on the Individual and Population Dynamics**

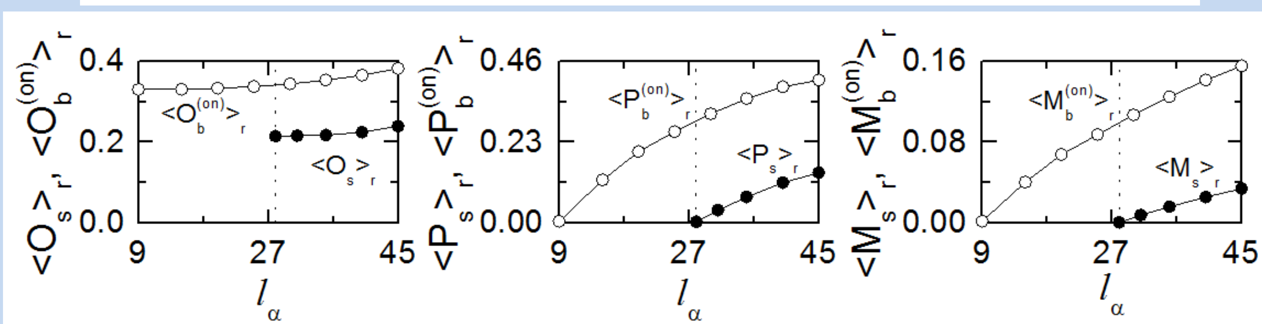
As l_α is increased, ensemble-averaged mean bursting rate (MBR) and mean spiking rate (MSR) increase.

⇒ Occupation degree of bursting and intraburst spiking increase.

As l_α is increased, distributions of MBR and MSR are reduced.

⇒ Pacing degree of bursting and intraburst spiking increase.

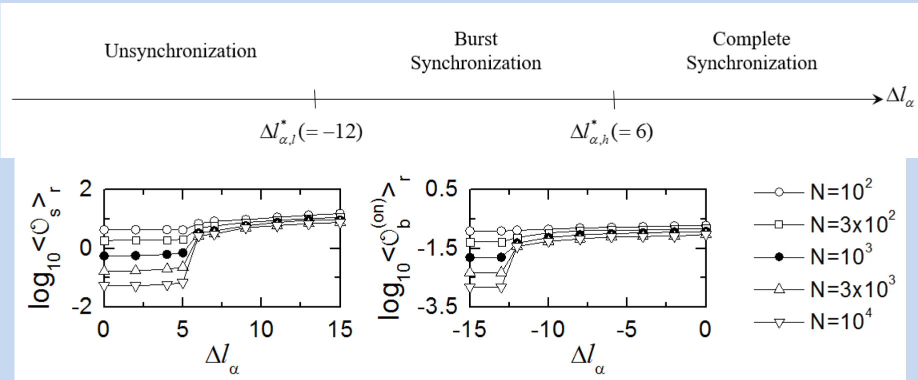


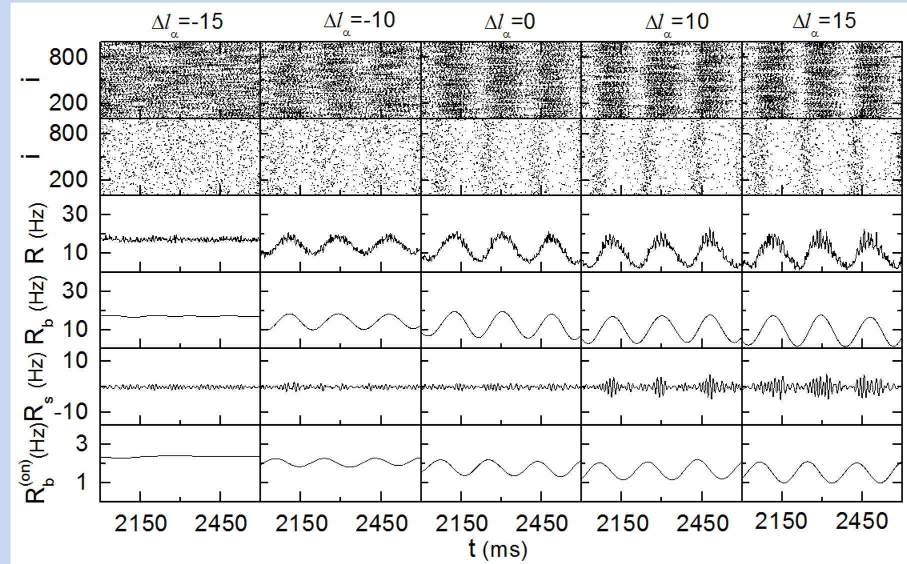


Effect of Δl_α on Burst and Spike Synchronization

$(I_{DC}=1.4, J=4, D=0.06, \tilde{l}_\alpha=20, l_\alpha^{(in)}=\tilde{l}_\alpha+\Delta l_\alpha, \& \; l_\alpha^{(out)}=\tilde{l}_\alpha-\Delta l_\alpha)$

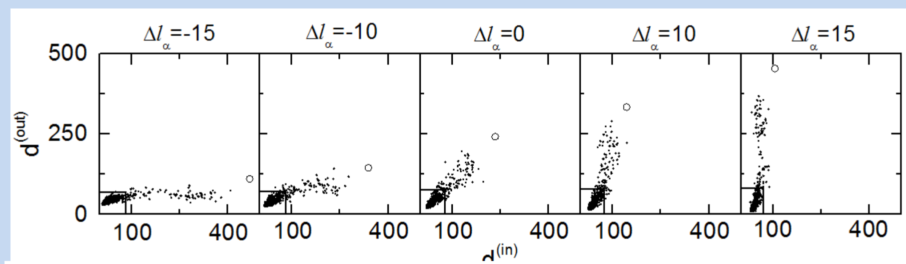
- **Burst and Complete Synchronization**

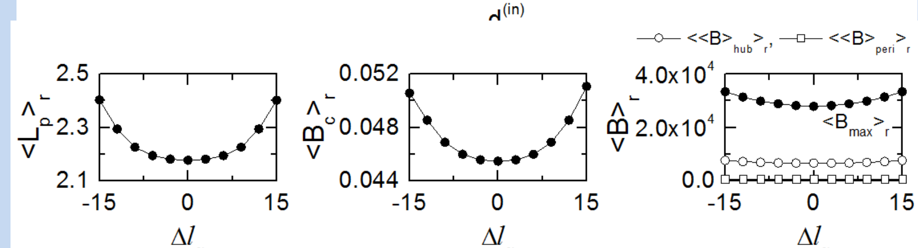




- **Effect of Δl_α on the Network Topology**

As $|\Delta l_\alpha|$ is increased, L_p increases.
B_{max} of head hub is much more increased than the average centralities of the secondary hubs and the peripheral nodes.
$\rightarrow$ B_c increases.
$\Rightarrow$ Efficiency of communication between nodes becomes better, which may lead to increase in the degree of burst and spike synchronization.





Effect of Δl_α on Burst and Spike Synchronization

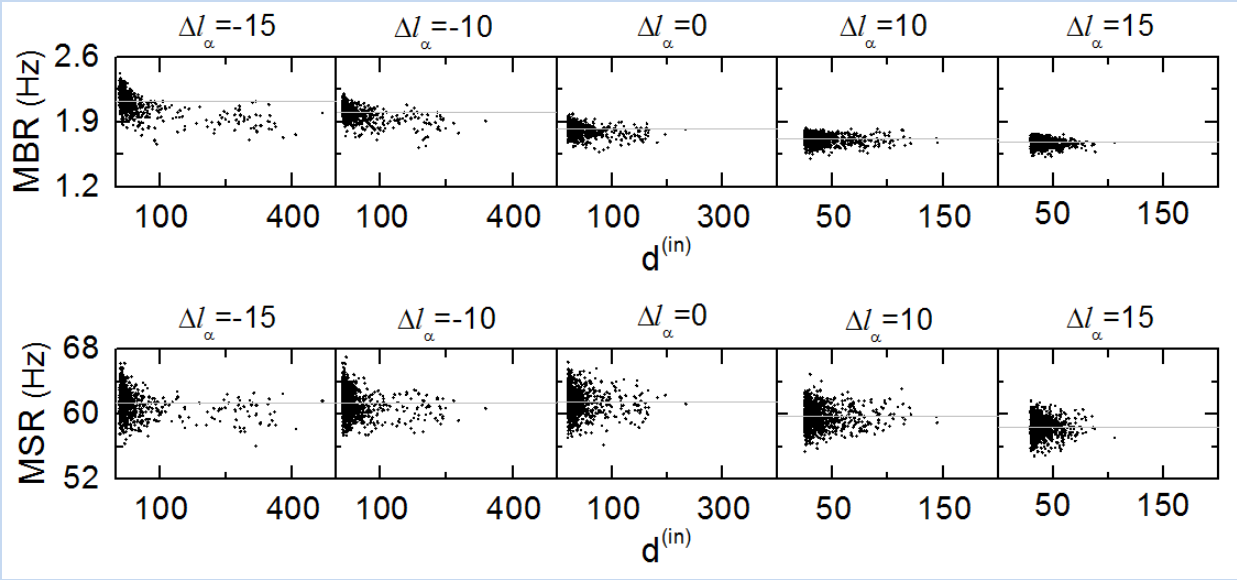
- **Effect of l_α on the Individual and Population Dynamics**

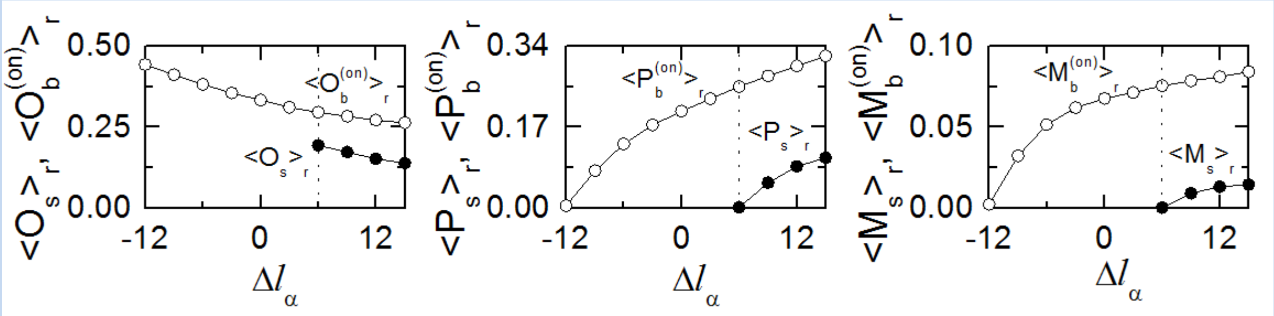
  As Δl_α is increased, ensemble-averaged MBR and MBR decrease.

  ⇒ Occupation degree of bursting and intraburst spiking decrease.

  As l_α is increased, distributions of MBR and MSR are reduced.

  ⇒ Pacing degree of bursting and intraburst spiking increase.

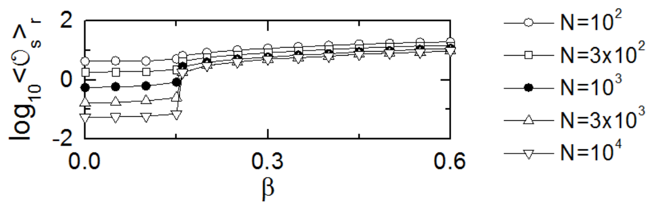


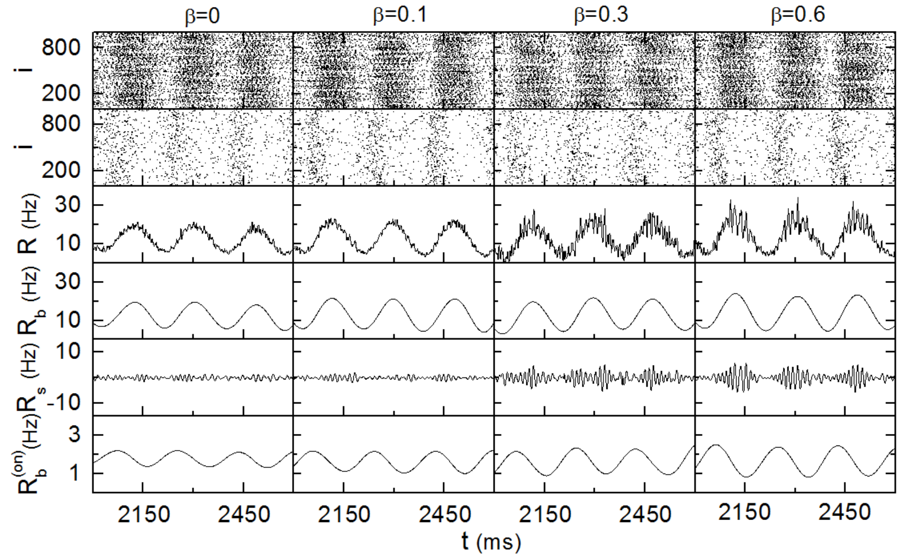


Effect of β on Burst and Spike Synchronization

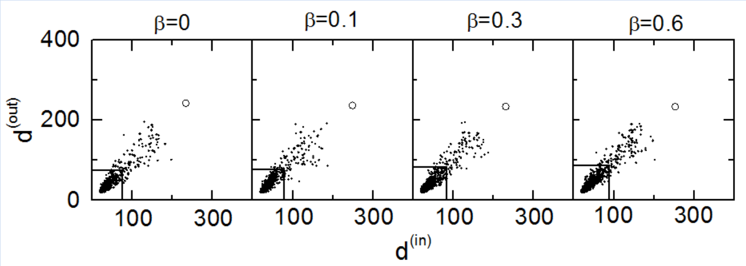
$(I_{DC}=1.4, J=4, D=0.06, \; l_\alpha^{(in)}=l_\alpha^{(out)}=\tilde{l}_\alpha=20, \; \& \; l_\beta=5)$

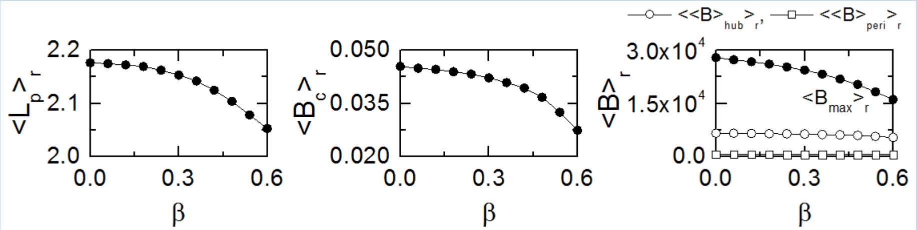
- **Burst and Complete Synchronization**
  Transition to complete synchronization: $\beta^*(\simeq 0.16)$





- **Effect of β on the Network Topology**
  As β is increased, L_p decreases.
  B_{max} of head hub is much more decreased than the average centralities of the secondary hubs and the peripheral nodes. → B_c decreases.
  ⇒ Efficiency of communication between nodes becomes better, which may lead to increase in the degree of burst and spike synchronization.



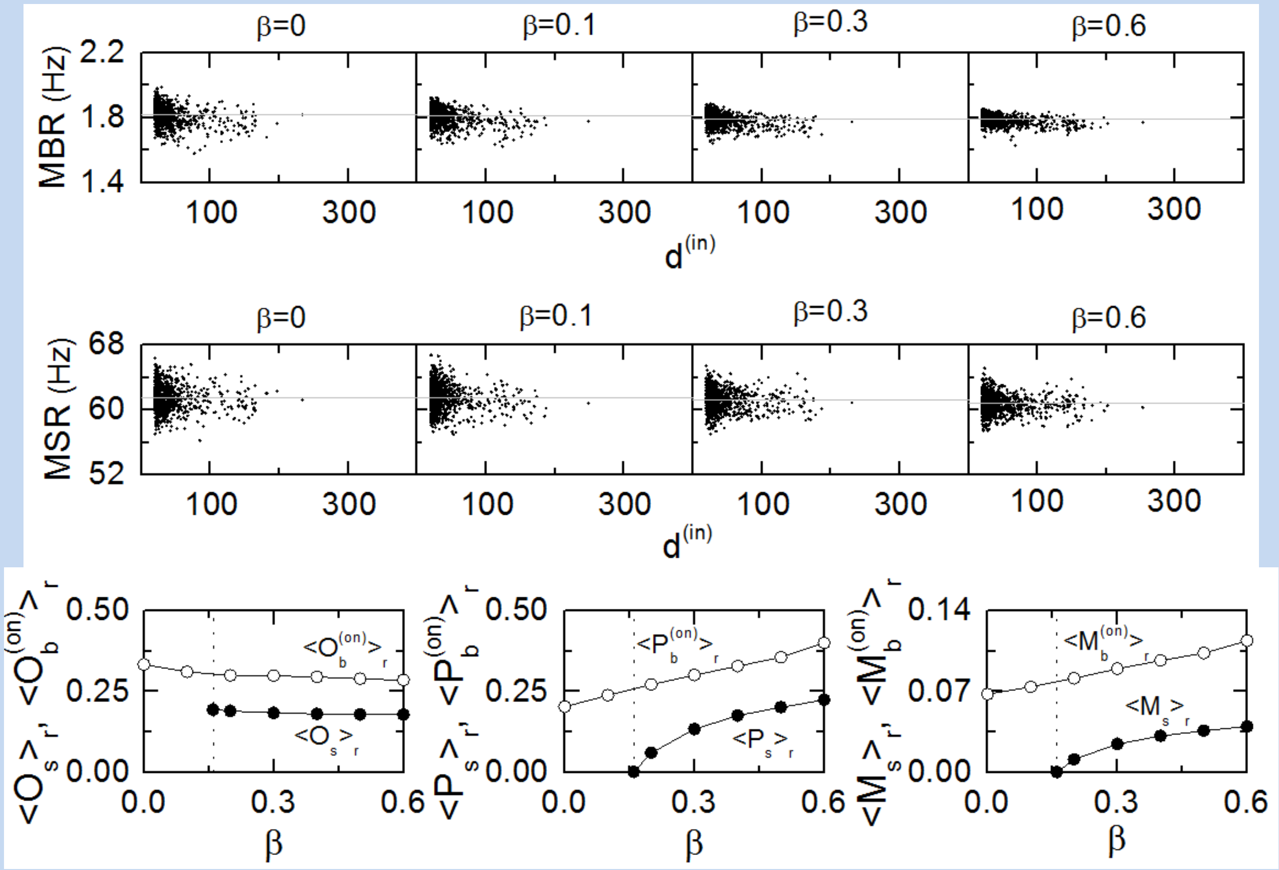


Effect of β on Burst and Spike Synchronization

- **Effect of β on the Individual and Population Dynamics**

  As β is increased, ensemble-averaged MBR and
  MSR decrease slowly. ⇒ Occupation degree of bursting and intraburst spiking decrease slowly.

  As β is increased, distributions of MBR and MSR are reduced.
  ⇒ Pacing degree of bursting and intraburst spiking increase.



Summary

- **Investigation of Burst and Spike Synchronization in Directed SFN of Bursting Neurons**
  - Emergence of Burst and Complete Synchronization
  - Characterization of Burst and Spike Synchronization in terms of Realistic Bursting and Spiking Order Parameters and Statistical-Mechanical Measures

- **Effect of Network Architecture on the Burst and Spike Synchronization**
  With increasing l_α, Δl_α, and β, pacing degree of burst and spike synchronization increase.