

Approximating Temporal Betweenness/Closeness with Temporal GNNs *

1 Related Work and Motivation

The *TATKC* model [4] introduced a temporal graph neural network (GNN) for approximating Temporal Katz Centrality (TKC), leveraging a time-aware attention mechanism followed by a downstream MLP. While *TATKC* performs effectively in predicting TKC, it is less suited for capturing Temporal Betweenness Centrality due to its inherently path-centric nature, which demands richer structural information. Specifically, *TATKC*'s reliance on raw node embeddings and temporal attention neglects crucial mid-path signals that are essential for identifying nodes with high temporal betweenness.

Motivated by these limitations, we propose two new models that extend the learning-based GNN paradigm to approximate path-based temporal centrality measures: the *TSBM* model for Temporal Shortest Betweenness Centrality and the *TSFMBM* model for Temporal Shortest-Foremost Betweenness Centrality. Our models incorporate features specifically designed to capture path relevance and intermediate-node influence, addressing the representational gaps observed in *TATKC*.

Formal definitions of temporal graphs and temporal betweenness centrality are provided in Appendices A.

2 Integration of the new node feature: `ptd_feat`

In the multi-layer perceptron (MLP) architecture, an additional scalar feature `ptd_feat` (representing the pass-through degree [1]), which basically it counts how many temporal paths of length 2 pass through a node, is incorporated alongside the primary node feature `src_feat`. The `src_feat` is of dimension $[B, 128]$, where B denotes the batch size, while the `ptd_feat` is a scalar for each node ($[B, 1]$).

2.1 MLP Architecture

In highly imbalanced temporal graphs where only a small fraction of nodes have non-zero betweenness centrality, models must be able to sharply distinguish important from unimportant nodes. We compare two strategies for incorporating **pass-through degree (ptd)** as an additional feature: *Concatenation* and *Feature-wise Linear Modulation (FiLM)* [2].

- **Concatenation (CONCAT)**: Here, the ptd feature is concatenated with the original node feature, treating it as an additional input. This straightforward approach allows the model to learn the importance of ptd during training but may not provide fine-grained control over its influence.
- **FiLM**: FiLM applies feature-wise affine transformations to the node features, conditioned on the ptd feature. This allows for more nuanced modulation, enabling the model to adaptively scale and shift features based on ptd, potentially capturing more complex relationships.

For the FiLM modulation pathway, `ptd_feat` is passed through `ptd_scale_proj` and `ptd_bias_proj`, each projecting $[B, 1] \rightarrow [B, 128]$. These projected vectors serve as the `scale` and `bias` parameters in the FiLM operation: the modulation is computed as `modulated_feat = src_feat * scale + bias`, preserving the original shape $[B, 128]$.

*The source code is available on <https://github.com/filipposchr/TBM>

In parallel, the `ptd_feat` is also processed through `ptd_proj`, a nonlinear projection with a ReLU activation and dropout, to produce another $[B, 128]$ vector. This output is then concatenated with the `modulated_feat`, resulting in a combined feature of shape $[B, 256]$.

The concatenated feature is subsequently passed through `input_proj`, which maps it back down to a `final_dim` of 128, maintaining dimensional compatibility for the downstream MLP. Finally, the output of shape $[B, 128]$ is processed by a deep MLP and projected to a single scalar per node via a final linear layer, resulting in an output of shape $[B, 1]$, which is then squeezed to $[B]$ for compatibility with standard loss functions and evaluation.

3 Loss function

The default model, **TATKC**, utilizes a pairwise ranking loss function, implemented in `loss_cal` to train the model for approximating TKC ranking scores. This function relies on margin ranking loss, which randomly samples node pairs and encourages the model to preserve correct ordering by scoring higher ground-truth nodes above lower ones.

4 Experiments

Hyper-parameters. The model is conducted with a learning rate of 0.01 for 15 epochs, with the node and time embedding dimension as 128 and number of neighbor samples to 20 (same as TATKC model).

4.1 Experimental Setup

Datasets. We utilize 13 real datasets from Konect¹ and Network Repository² for evaluation. The statistics are summarized in Table 1. The training dataset consists of 48 real-world datasets from Konect, each ranging from 1000 to 12000 nodes (see Table 1).

Dataset	$ V $	$ E $	$ T $
mathoverflow	24,759	390,414	389,952
facebook-wall	35,817	198,028	194,904
topology	16,564	198,038	32,823
mlwikiquote	43,889	142,340	137,389
plwikiquote	581,646	1,472,273	1,452,278
digg-reply	30,398	87,627	83,943
SMS	44,090	544,607	467,838
retweet-pol	18,469	61,157	60,501
slashdot-reply	51,083	139,789	89,862
wang-amazon	26,911	29,062	2,175
mgwikipedia	220,064	750,811	736,680
tgwiktionary	33,968	81,516	67,065
ltwiktionary	689,678	1,693,277	1,633,334

Table 1: Statistics of the testing datasets.

Evaluation Metrics. We evaluate the model’s effectiveness in terms of top- $N\%$ accuracy, Kendall’s tau correlation and Jaccard index.

1. **Top-K Accuracy** is defined as:

$$\text{Top-}N\% = \frac{|\text{Top-}N\% \text{ predicted nodes} \cap \text{Top-}N\% \text{ true nodes}|}{\lceil |V| \times N\% \rceil}$$

¹Konect is available at <http://konect.cc/>

²Network Repository is available at <https://networkrepository.com/networks.php>

where $|V|$ is the number of nodes and $\lceil \cdot \rceil$ denotes the ceiling function. This metric measures the fraction of correctly predicted top- $N\%$ nodes compared to the ground truth, and is commonly used to evaluate effectiveness in identifying highly central nodes.

Evaluation Code Behavior:

The function `compute_topk_metrics_all` implements this definition precisely:

- $N = \text{len}(\text{preds})$ corresponds to $|V|$.
- $\text{topk} = \max(1, \text{math.ceil}(N * (k / 100)))$ implements $\lceil |V| \cdot N\% \rceil$.
- `torch.topk(preds, topk)` selects the top- K predicted nodes.
- `torch.topk(labels, topk)` selects the top- K true (ground-truth) nodes.
- The intersection of these sets is computed, and the final metric is:

$$\frac{|\text{predicted top-}K \cap \text{true top-}K|}{K}$$

2. **Weighted Kendall Tau (WKT)** is a rank-based correlation metric that measures the ordinal association between two sequences. In this evaluation, it is used to assess how well the predicted ranking of nodes aligns with the ground truth ranking based on temporal betweenness.

- (a) **Tiebreaking Strategy:** The ranking procedure uses the function `rank_with_id_tiebreak(values)`, with the "ordinal" method, which assigns unique integer ranks based on the order of appearance (row index) when ties occur. This avoids ambiguity from tied ranks, ensuring that every element receives a unique rank, which is required for computing Kendall tau consistently.

- (b) **Computation of WKT** (function `compute_kendall_tau`):

- i. **Standard WKT over all nodes** is computed as:

```
label_ranked_full = rank_with_id_tiebreak(labels)
pred_ranked_full = rank_with_id_tiebreak(preds)
kt_full, _ = weightedtau(pred_ranked_full, label_ranked_full)
```

This version compares the full ranked list of predictions and ground truth across all nodes, regardless of whether the ground truth is zero or not.

- ii. **Filtered WKT on non-zero ground truth values only** is computed as:

```
nonzero_mask = labels > 0
label_filtered = labels[nonzero_mask]
pred_filtered = preds[nonzero_mask]
label_ranked_filt = rank_with_id_tiebreak(label_filtered)
pred_ranked_filt = rank_with_id_tiebreak(pred_filtered)
kt_filt, _ = weightedtau(pred_ranked_filt, label_ranked_filt)
```

This filtered variant restricts the correlation calculation to the subset of nodes with non-zero ground truth centrality. This is important in sparse graphs where most nodes have zero temporal betweenness, which would otherwise dominate the ranking and obscure differences among important nodes.

- (c) The WKT values reported in Table 3 and Table 5 correspond to the *filtered* WKT computed only on nodes with non-zero ground truth (defined in 2.a.ii). The standard WKT computed over all nodes is consistently higher.

- (d) **Interpretation:**

- A higher `kt_full` indicates better alignment in global ranking across all nodes.
- A higher `kt_filt` reflects better ranking precision among the truly important (non-zero) nodes.

- In datasets where many nodes have a ground truth value of zero, WKT computed over all nodes can be lower if the model assigns different (noisy) prediction scores to those zero-value nodes (e.g., x , y , z). This introduces noise into the global ranking and reduces Kendall tau. In contrast, WKT computed only over the non-zero ground truth nodes ignores these irrelevant variations and can yield a higher score. This filtered WKT better reflects the model’s ranking quality on the meaningful part of the distribution. When the model assigns the same predictions to all zero-labeled nodes, the all-node and non-zero-only WKT scores tend to be closer.

3. **Jaccard Index** is defined as:

$$J(A, B) = \frac{|A \cap B|}{|A \cup B|}$$

where A and B are two sets. In the context of this model evaluation, A represents the set of predicted important nodes and B the ground truth important nodes.

(a) **Computation of Jaccard**

The following lines compute the Jaccard index in the `compute_topk_metrics_all` function :

```
pred_full_set = set(torch.topk(preds, len(true_full_set)).indices.tolist())
full_jacc = len(pred_full_set & true_full_set) / len(pred_full_set | true_full_set)
```

This corresponds to the following steps:

- `true_full_set` contains all node indices for which the ground truth value is greater than zero (i.e., nodes deemed important by the centrality ground truth).
- `pred_full_set` is constructed by selecting the same number of top predicted nodes as there are in the true set, ensuring fair comparison.
- The numerator computes the size of the intersection between the predicted and true sets.
- The denominator computes the size of the union of the two sets.

(b) **Interpretation:**

The Jaccard Index here captures the global agreement between the predicted and true sets of important nodes—regardless of ranking—by comparing the overlap of non-zero centrality predictions with ground truth. A higher Jaccard value indicates better alignment between model predictions and actual influential nodes.

4.2 Experimental Result

We evaluate two models: **TSBM** (Temporal Shortest Betweenness Model), which focuses on temporal shortest-path betweenness (sh), and **TSFMBM** (Temporal Shortest-Foremost Betweenness Model), designed for temporal shortest-foremost betweenness (sfm). Specifically, we evaluate the performance of four model variants: **TSBM_C**, **TSBM_{CF}** (see Table 2 and Table 3), and their shortest-foremost equivalents, **TSFMBM_C** and **TSFMBM_{CF}** (see Table 4 and Table 5). Evaluation is conducted using Top-N accuracy, Jaccard index, and Weighted Kendall’s Tau (WKT) metrics across a diverse set of real-world temporal graphs. The **C** variants rely solely on feature concatenation, while the **CF** variants extend this setup with FiLM-based conditioning over the concatenated features.

For comparison, we include WKT scores for the MANTRA [3] model, a recent approximation-based approach for temporal betweenness estimation. The models are trained using the standard `loss_cal` function.

Some scores for the MANTRA model are omitted due to the extremely low connectivity of certain temporal graphs (e.g., 0.0000096 in `tgwiktionary`), where the vast majority of nodes have zero betweenness (only 235 out of 33,968 nodes have non-zero temporal betweenness). In such sparse graphs, achieving a reliable approximation would require an extremely small ε (i.e., the approximation accuracy parameter), for example $\varepsilon < 0.000009$, which makes MANTRA either impractical to compute or too inaccurate to be meaningful.

Dataset	Top-1%			Top-5%			Top-10%			Top-20%			Jaccard		
	TSBM _c	TSBM _{CF}	MANTRA	TSBM _c	TSBM _{CF}	MANTRA	TSBM _c	TSBM _{CF}	MANTRA	TSBM _c	TSBM _{CF}	MANTRA	TSBM _c	TSBM _{CF}	MANTRA
mathoverflow	0.86	0.5	0.85	0.82	0.82	0.7	0.76	0.76	0.57	0.8	0.8	0.39	0.95	0.94	0.54
facebook	0.56	0.56	0.85	0.65	0.65	0.83	0.7	0.7	0.79	0.77	0.78	0.67	0.9	0.9	0.69
topology	0.7	0.66	0.68	0.66	0.66	0.65	0.68	0.67	0.55	0.7	0.7	0.39	0.78	0.79	0.44
mlwikiquote	0.76	0.67	0.9	0.84	0.84	0.56	0.8	0.82	0.34	0.63	0.85	0.49	0.77	0.83	0.49
plwikiquote	0.68	0.68	0.49	0.83	0.83	0.04	0.82	0.94	0.08	0.49	0.97	0.48	0.93	0.93	0.47
digg_reply	0.65	0.65	0.88	0.7	0.7	0.79	0.75	0.75	0.6	0.93	0.92	0.35	0.99	0.99	0.67
SMS	0.64	0.64	0.56	0.63	0.64	0.22	0.67	0.67	0.15	0.85	0.99	0.15	0.83	0.86	0.42
rt-pol	0.75	0.75		0.77	0.77		0.91	0.91		0.65	0.87		0.96	0.96	
slashdot	0.81	0.81	0.75	0.82	0.82	0.67	0.84	0.84	0.41	0.85	0.91	0.39	0.9	0.91	0.59
wamazon	0.95	0.95	0.61	0.72	1	0.74	0.87	1	0.87	0.92	1	0.93	1	1	0.64
mgwikipedia	0.84	1		0.18	0.99		0.11	0.99		0.11	0.99		0.95	0.95	
tgwiktionary	0.84	1		0.19	0.99		0.19	0.99		0.23	0.99		0.99	0.99	
ltwiktionary	0.31	1		0.11	0.99		0.13	0.99		0.2	0.99		0.99	0.98	

Table 2: Top-N accuracy and Jaccard similarity for the **TSBM** (Temporal Shortest Betweenness Model) on a diverse set of real-world temporal graphs. **TSBM_c** refers to the model variant using feature concatenation only, while **TSBM_{CF}** applies FiLM-based conditioning over concatenated features. Bold values highlight the best performance across the GNN methods.

Dataset	WKT (all nodes)			WKT (non zero)		
	TSBM _c	TSBM _{CF}	MANTRA	TSBM _c	TSBM _{CF}	MANTRA
mathoverflow	0.92	0.94	0.75	0.42	0.87	0.86
facebook	0.91	0.92	0.83	0.86	0.86	0.9
topology	0.91	0.91	0.73	0.84	0.83	0.82
mlwikiquote	0.8	0.95	0.76	0.8	0.79	0.86
plwikiquote	0.86	0.98	0.58	0.83	0.83	0.82
digg_reply	0.91	0.97	0.84	0.85	0.85	0.9
SMS	0.89	0.93	0.63	0.84	0.85	0.74
rt-pol	0.9	0.98		0.31	0.87	
slashdot	0.94	0.98	0.83	0.9	0.9	0.86
wamazon	0.94	0.99	0.87	0.86	0.86	0.8
mgwikipedia	0.83	0.99		0.83	0.81	
tgwiktionary	0.59	0.99		0.9	0.83	
ltwiktionary	0.7	0.99		0.92	0.85	

Table 3: Standard (all nodes) and filtered WKT scores for the **TSBM** (Temporal Shortest Betweenness Model) computed using the ordinal tie-breaking strategy. The filtered scores consider only nodes with non-zero ground truth values. Results are reported for the **TSBM_{CF}** variant.

Dataset	Top-1%			Top-5%			Top-10%			Top-20%			Jaccard		
	TSFMBM _c	TSFMBM _{CF}	MANTRA	TSFMBM _c	TSFMBM _{CF}	MANTRA	TSFMBM _c	TSFMBM _{CF}	MANTRA	TSFMBM _c	TSFMBM _{CF}	MANTRA	TSFMBM _c	TSFMBM _{CF}	MANTRA
mathoverflow	0.85	0.58		0.84	0.84		0.79	0.79		0.8	0.8		0.95	0.95	
facebook	0.55	0.55	0.83	0.65	0.65	0.81	0.7	0.7	0.76	0.77	0.77	0.61	0.9	0.9	0.65
topology	0.72	0.68	0.75	0.68	0.68	0.66	0.7	0.7	0.54	0.71	0.71	0.39	0.77	0.8	0.46
mlwikiquote	0.76	0.73	0.90	0.8	0.81	0.59	0.76	0.79	0.41	0.52	0.52	0.63	0.63	0.67	0.46
plwikiquote	0.66	0.66	0.5	0.74	0.74	0.04	0.64	0.64	0.24	0.4	0.37	0.53	0.72	0.73	0.56
digg_reply	0.64	0.64	0.85	0.7	0.7	0.68	0.74	0.74	0.43	0.93	0.93	0.27	0.98	0.98	0.58
SMS	0.65	0.66	0.83	0.64	0.64	0.81	0.67	0.67	0.76	0.85	0.85	0.61	0.84	0.86	0.65
rt-pol	0.75	0.75	0.82	0.77	0.77	0.5	0.91	0.91	0.27	0.63	0.62	0.51	0.92	0.92	0.62
slashdot	0.79	0.79	0.74	0.81	0.81	0.61	0.84	0.84	0.37	0.82	0.82	0.37	0.88	0.89	0.56
wamazon	0.96	0.96	0.83	0.58	0.55	0.81	0.71	0.69	0.76	0.84	0.81	0.61	0.99	0.99	0.65
mgwikipedia	0.84	0.84		0.17	0.15		0.1	0.12		0.11	0.13		0.76	0.76	
tgwiktionary	0.84	0.84		0.19	0.2		0.18	0.17		0.22	0.25		0.91	0.91	
ltwiktionary	0.11	0.13		0.07	0.03		0.15	0.3		0.24	0.43		0.92	0.92	

Table 4: Top-N accuracy and Jaccard similarity for the **TSFMBM** (Temporal Shortest-Foremost Betweenness Model) on a diverse set of real-world temporal graphs. **TSFMBM_c** refers to the model variant using feature concatenation only, while **TSFMBM_{CF}** applies FiLM-based conditioning over concatenated features. Bold values highlight the best performance across the GNN methods.

Dataset	WKT (all nodes)			WKT (non zero)		
	TSFMBM _C	TSFMBM _{CF}	MANTRA	TSFMBM _C	TSFMBM _{CF}	MANTRA
mathoverflow	0.92	0.9		0.9	0.88	
facebook	0.91	0.91	0.82	0.86	0.86	0.89
topology	0.9	0.9	0.73	0.85	0.84	0.83
mlwikiquote	0.73	0.72	0.80	0.8	0.8	0.83
plwikiquote	0.82	0.72	0.63	0.79	0.79	0.79
digg_reply	0.92	0.91	0.8	0.85	0.85	0.86
SMS	0.89	0.89	0.82	0.85	0.85	0.89
rt-pol	0.89	0.86	0.81	0.86	0.85	0.86
slashdot	0.95	0.93	0.82	0.9	0.9	0.84
wamazon	0.98	0.9	0.82	0.86	0.86	0.89
mgwikipedia	0.8	0.7		0.81	0.8	
tgwiktionary	0.63	0.63		0.87	0.87	
ltwiktionary	0.62	0.66		0.78	0.77	

Table 5: Standard (all nodes) and filtered WKT scores for the **TSFMBM** (Temporal Shortest-Foremost Betweenness Model) computed using the ordinal tie-breaking strategy. The filtered scores consider only nodes with non-zero ground truth values. Results are reported for the TSFMBM_{CF} variant.

5 Integration of a Third Node Feature: arrival_feat

To enhance the predictive performance of **TSFMBM** (Temporal Shortest-Foremost Betweenness Model)—whose results using only two node features are shown in Table 4 and Table 5—we introduce a third scalar feature, **arrival_feat**, which encodes the earliest time at which each node becomes reachable.

While the core representation **src_feat** captures structural and temporal context, and **ptd_feat** reflects a node’s pass-through frequency, **arrival_feat** introduces a notion of temporal urgency, indicating how early a node can be accessed within the temporal graph. This information is particularly relevant for shortest-foremost paths, which prioritize early arrival over minimal hop count.

Both **ptd_feat** and **arrival_feat** are projected from shape $[B, 1]$ to $[B, 128]$ and concatenated with **src_feat** (of shape $[B, 128]$), resulting in a unified input of shape $[B, 384]$ for the MLP.

We implement this design in two architectural variants:

- **MLPWithThreeFeatC**, which directly concatenates the projected features, corresponding to the TSFMBM_C model;
- **MLPFilmThreeFeatCF**, which applies FiLM-style modulation to **src_feat** using **ptd_feat**, followed by concatenation with both projected **ptd_feat** and **arrival_feat**, corresponding to the TSFMBM_{CF} model.

Results incorporating the **arrival_feat** feature are presented in Table 6 and Table 7.

Dataset	Top-1%		Top-5%		Top-10%		Top-20%		Jaccard	
	TSFMBM _C	TSFMBM _{CF}	TSFMBM _C	TSFMBM _{CF}	TSFMBM _C	TSFMBM _{CF}	TSFMBM _C	TSFMBM _{CF}	TSFMBM _C	TSFMBM _{CF}
mathoverflow	0.46	0.54	0.84	0.84	0.79	0.79	0.80	0.80	0.95	0.95
facebook	0.54	0.54	0.65	0.65	0.70	0.70	0.77	0.77	0.90	0.90
topology	0.48	0.51	0.67	0.67	0.70	0.70	0.71	0.72	0.78	0.75
mlwikiquote	0.73	0.67	0.81	0.81	0.78	0.75	0.72	0.71	0.65	0.63
plwikiquote	0.66	0.66	0.74	0.74	0.77	0.77	0.86	0.86	0.73	0.73
digg_reply	0.63	0.64	0.70	0.70	0.74	0.74	0.93	0.93	0.98	0.98
SMS	0.66	0.65	0.64	0.64	0.68	0.68	0.85	0.85	0.82	0.82
rt-pol	0.73	0.74	0.77	0.77	0.91	0.91	0.85	0.90	0.93	0.93
slashdot	0.80	0.79	0.81	0.82	0.84	0.84	0.82	0.88	0.88	0.88
wamazon	0.96	0.97	0.90	0.99	0.93	0.99	0.96	0.99	0.99	0.99
mgwikipedia	0.99	1	0.92	0.94	0.97	0.98	0.97	0.99	0.77	0.76
tgwiktionary	0.99	1	0.91	0.98	0.97	0.99	0.97	0.99	0.93	0.93
ltwiktionary	0.99	1	0.91	0.99	0.95	0.99	0.96	0.99	0.92	0.92

Table 6: Top-N accuracy and Jaccard similarity for the **TSFMBM** (Temporal Shortest-Foremost Betweenness Model) - integrating **arrival_feat** - on a diverse set of real-world temporal graphs. TSFMBM_C refers to the model variant using feature concatenation only, while TSFMBM_{CF} applies FiLM-based conditioning over concatenated features. Bold values highlight the best performance across the GNN methods.

Dataset	WKT (all nodes)		WKT (non zero)	
	TSFMBM _C	TSFMBM _{CF}	TSFMBM _C	TSFMBM _{CF}
mathoverflow	0.94	0.94	0.86	0.87
facebook	0.92	0.92	0.86	0.86
topology	0.90	0.90	0.81	0.82
mlwikiquote	0.88	0.88	0.78	0.78
plwikiquote	0.94	0.94	0.78	0.78
digg_reply	0.97	0.97	0.85	0.85
SMS	0.93	0.93	0.85	0.85
rt-pol	0.98	0.98	0.86	0.86
slashdot	0.97	0.97	0.89	0.89
wamazon	0.99	0.99	0.86	0.85
mgwikipedia	0.97	0.98	0.80	0.80
tgwiktionary	0.99	0.99	0.86	0.80
ltwiktionary	0.98	0.99	0.83	0.82

Table 7: Standard (all nodes) and filtered WKT scores for the **TSFMBM** (Temporal Shortest-Foremost Betweenness Model) - integrating **arrival_feat** - computed using the ordinal tie-breaking strategy. The filtered scores consider only nodes with non-zero ground truth values. Results are reported for the TSFMBM_C and TSFMBM_{CF} variant.

5.1 Supremum Deviation and MAE Analysis

In addition to ranking-based metrics, we report the Supremum Deviation (SD) and Mean Absolute Error (MAE) to quantify the magnitude of prediction errors for temporal betweenness centrality. The Supremum Deviation measures the absolute difference between the mean of the predicted values and the mean of the ground truth values, reflecting any global bias in the model’s scale of predictions. Higher SD values indicate that the model systematically overestimates or underestimates the overall magnitude of betweenness scores. Conversely, the MAE assesses the average absolute difference between predicted and true values across all nodes, capturing local prediction accuracy. Low MAE values suggest the model closely approximates the node-level centrality, even if the global scale may be biased.

The SD values indicate that the model exhibits a noticeable global bias in its predictions, while the very low Mean Absolute Error shows that, on average, the model is making highly accurate node-level predictions.

The results, summarized in Table 9, show that although the SD ranges from approximately 0.18 to 0.60, the normalized MAE remains extremely low across datasets, highlighting the strong local accuracy of the model despite some bias in the overall scale of predictions.

Dataset	TSBM _C			TSBM _{CF}		
	Pred ≤ 0 , True > 0	SD	MAE	Pred ≤ 0 , True > 0	SD	MAE
mathoverflow	3402	0.000396	0.0012827	0	0.307	0.00128
facebook	7154	0.03321	0.0037232	0	0.3569	0.00372
topology	3413	0.00069	0.0015826	0	0.31619	0.001583
mlwikiquote	296	0.05606	0.0035087	0	0.06885	0.0030
plwikiquote	1347	4.82×10^{-5}	9.83×10^{-5}	0	0.0598	9.8361×10^{-5}
digg_reply	3048	0.00749	0.001807	0	0.1478	0.001806
SMS	6764	0.015269	0.001268	0	0.19307	0.001267
rt-pol	1109	0.002895	0.001557	0	0.07953	0.00155
slashdot	3522	0.000608	0.000977	0	0.120552	0.000977
wamazon	132	0.02238	0.000781	0	0.008125	0.0004275
mgwikipedia	891	3.70×10^{-5}	2.33×10^{-5}	0	0.005171	2.30×10^{-5}
tgwiktionary	148	0.002329	0.000429	0	0.00469	0.00026
ltwiktionary	312	7.32×10^{-5}	9.75×10^{-6}	0	0.0020	1.04×10^{-5}

Table 8: The table reports (i) the number of nodes with predicted betweenness values ≤ 0 while the ground truth betweenness is > 0 , (ii) the Supremum Deviation (SD), and (iii) the Mean Absolute Error (MAE) for the **TSBM** (Temporal Shortest Betweenness Model) across the testing datasets.

Dataset	TSFMBM _C			TSFMBM _{CF}		
	Pred ≤ 0 , True > 0	SD	MAE	Pred ≤ 0 , True > 0	SD	MAE
mathoverflow	0	0.517189	0.001508	33	0.3431932	0.001508
facebook	0	0.59934	0.003499	665	0.416918	0.003499
topology	0	0.4679802	0.001695	26	0.377038	0.001695
mlwikiquote	0	0.343673	0.003043	0	0.090904	0.003077
plwikiquote	0	0.274652	0.000107	119	0.065472	0.000107
digg_reply	0	0.4430229	0.001771	732	0.16643	0.001771
SMS	0	0.4422315	0.0011279	852	0.20441	0.0011280
rt-pol	0	0.321965	0.001571	264	0.09095	0.00157
slashdot	0	0.415216	0.0009534	50	0.13331	0.00095
wamazon	0	0.17757	0.0004942	36	0.00914	0.000428
mgwikipedia	0	0.235975	1.96×10^{-5}	234	0.00601	1.96×10^{-5}
tgwiktionary	0	0.1853245	0.0002576	44	0.00574	0.000223

Table 9: The table reports (i) the number of nodes with predicted betweenness values ≤ 0 while the ground truth betweenness is > 0 , (ii) the Supremum Deviation (SD), and (iii) the Mean Absolute Error (MAE) for the **TSFMBM** (Temporal Shortest Foremost Betweenness Model) across the testing datasets.

5.1.1 Discussion

1. For the **TSFMBM** (Temporal Shortest-Foremost Betweenness Model), the results presented in Table 6 and Table 7, which incorporate the `arrival_feat` feature as an additional node input, demonstrate improved performance compared to the baseline results in Table 4 and Table 5 that use only the two node features (`src_feat` and `ptd_feat`). Specifically, the inclusion of the arrival feature leads to consistently higher Top-k Jaccard scores and Weighted Kendall Tau values.
2. In highly imbalanced settings, it is possible for the Top- k accuracy to decrease as k increases, contrary to intuition. This counterintuitive behavior typically occurs when the ground truth contains a large number of zero-valued targets, and the model assigns non-zero (noisy) scores to these unimportant nodes. As k increases, the prediction set may include more of these noisy false positives, thereby reducing precision. While the Top-1% predictions often remain focused on genuinely high-centrality nodes, the wider Top-5% or Top-10% sets can become diluted by misranked low-importance nodes. For instance, this is observed when evaluating the model **TSBM_{CF}** on the **mathoverflow** dataset, where the Top-1% accuracy reaches 0.50, but the Top-5% drops to 0.82, with Top-10% and Top-20% further declining to 0.76 and 0.80, respectively. The large number of ground-truth-zero nodes in **mathoverflow**, combined with prediction variance among them, leads to reduced performance at broader thresholds despite a strong Top-1% accuracy.

6 Further Experiments

All the following experiments demonstrate a decline in performance across top-k prediction accuracy, Jaccard similarity, and weighted Kendall tau metrics.

6.1 Using only *src_feat*

We conduct experiments for predicting temporal shortest betweenness using only the node feature *src_feat*, as done in the baseline TATKC model [4].

From Table 10, we conclude that also *ptd_feat* is an essential feature, as its concatenation with *src_feat* results in higher accuracy when computing temporal shortest betweenness.

Dataset	Top-1%	Top-5%	Top-10%	Top-20%	Jaccard
mathoverflow	0.0524	0.3352	0.5178	0.6242	0.5127
facebook	0.0279	0.1787	0.2940	0.4595	0.6235
topology	0.0181	0.2280	0.3241	0.5044	0.6733
mlwikiquote	0.00	0.0545	0.1121	0.2109	0.0552
plwikiquote	0.0685	0.2678	0.3137	0.2820	0.1910
digg_reply	0.0362	0.2174	0.3610	0.5341	0.3830
SMS	0.0249	0.1365	0.2454	0.4135	0.3311
rt-pol	0.0162	0.2338	0.3422	0.3766	0.2245
slashdot	0.0861	0.3930	0.5434	0.6257	0.5150
wamazon	0.4389	0.6378	0.8086	0.8859	0.3143
mgwikipedia	0.0257	0.0391	0.0653	0.1064	0.0085
tgwiktionary	0.0072	0.0458	0.0828	0.1746	0.00
ltwiktionary	0.0193	0.0225	0.0376	0.0655	0.0014

Table 10: Top-N accuracy and Jaccard similarity for the **TSBM** (Temporal Shortest Betweenness Model) – using only *src_feat* as a node feature – on a diverse set of real-world temporal graphs.

6.2 Adding/removing *ptd_feat* and *arrival_feat*

In the following, we conduct experiments on **TSBM** and **TSFMBM** models, with and without the newly integrated features, to compare their performance. The results presented below indicate a decline in performance.

From Table 11, we conclude that *arrival_feat* is a redundant feature, as its inclusion results in lower accuracy when computing temporal shortest betweenness.

Dataset	Top-1%	Top-5%	Top-10%	Top-20%	Jaccard
mathoverflow	0.113	0.361	0.555	0.818	0.947
facebook	0.106	0.343	0.638	0.767	0.901
topology	0.006	0.479	0.642	0.701	0.791
mlwikiquote	0.697	0.855	0.767	0.624	0.745
plwikiquote	0.448	0.828	0.822	0.458	0.926
digg_reply	0.151	0.660	0.751	0.929	0.999
SMS	0.347	0.609	0.671	0.850	0.830
rt-pol	0.287	0.772	0.912	0.656	0.967
slashdot	0.317	0.775	0.841	0.847	0.897
wamazon	0.958	0.276	0.627	0.801	1.000
mgwikipedia	0.839	0.223	0.181	0.224	0.950
tgwiktionary	0.844	0.216	0.235	0.194	0.991
ltwiktionary	0.309	0.206	0.223	0.290	0.986

Table 11: Top-N accuracy and Jaccard similarity for the **TSBM** (Temporal Shortest Betweenness Model) with **TSBM_c** – using *src_feat*, *ptd_feat*, and *arrival_feat* as node features – on a diverse set of real-world temporal graphs.

From Table 12, we conclude that *ptd_feat* is an essential feature, necessary for achieving higher accuracy when computing temporal shortest-foremost betweenness.

Dataset	Top-1%	Top-5%	Top-10%	Top-20%	Jaccard
mathoverflow	0.359	0.002	0.013	0.086	0.118
facebook	0.022	0.006	0.021	0.109	0.171
topology	0.108	0.002	0.015	0.107	0.148
mlwikiquote	0.394	0	0.030	0.393	0
plwikiquote	0.492	0	0.229	0.513	0
digg_reply	0.082	0.013	0.030	0.093	0.060
SMS	0.098	0.010	0.037	0.098	0.089
rt-pol	0.184	0.004	0.021	0.375	0.019
slashdot	0.182	0.001	0.011	0.171	0.022
wamazon	0.435	0.606	0.809	0.892	0.271
mgwikipedia	1.000	0.768	0.891	0.931	0.613
tgwiktionary	1.000	0.731	0.874	0.922	0.889
ltwiktionary	1.000	0.959	0.979	0.988	0.907

Table 12: Top-N accuracy and Jaccard similarity for the **TSFMBM** (Temporal Shortest-Foremost Betweenness Model) with **TSFMBM_C** - using *src_feat* and *arrival_feat* (not using the *ptd_feat*) as node features - on a diverse set of real-world temporal graphs.

7 Temporal Closeness

Temporal Betweenness vs. Closeness Neighborhood Aggregation. For predicting **temporal betweenness centrality**, the model aggregates information from the **in-neighbors** of a node v at a given time t . Specifically, it considers all interactions arriving at v via time-respecting edges occurring strictly before t , thereby capturing how often v serves as an intermediary in temporal paths. In contrast, for predicting **temporal closeness centrality**, the architecture is modified to aggregate information from the **out-neighbors** of each node. That is, for a node v at time t , the model considers all edges originating from v with timestamps strictly greater than t . This change ensures that the model learns how efficiently a node can reach other nodes through time-respecting paths, which aligns with the definition of temporal closeness.

7.1 Temporal Fastest Closeness Model (TFCM)

Integration of a new node feature: out_deg_feat. For the prediction of the temporal fastest closeness an additional scalar feature, namely *out_deg_feat* (representing the temporal out degree for each node), is incorporated alongside the primary node feature *src_feat*.

Dataset	Top-1%	Top-5%	Top-10%	Top-20%	Jaccard
mathoverflow	0.88	0.89	0.88	0.87	1.00
facebook	0.65	0.72	0.76	0.80	1.00
topology	0.56	0.68	0.64	0.63	1.00
mlwikiquote	0.82	0.79	0.81	1.00	1.00
plwikiquote	0.73	0.72	1.00	1.00	1.00
digg_reply	0.51	0.58	0.59	0.69	1.00
SMS	0.71	0.76	0.79	0.80	1.00
rt-pol	0.39	0.46	0.59	0.83	1.00
slashdot	0.83	0.82	0.83	0.73	1.00
wamazon	0.16	0.28	0.33	0.32	1.00
mgwikipedia	1.00	0.91	0.96	0.97	1.00
tgwiktionary	1.00	1.00	1.00	1.00	1.00
ltwiktionary	1.00	1.00	1.00	1.00	1.00

Table 13: Top-N accuracy and Jaccard similarity for the **TFCM** (Temporal Fastest Closeness Model), using *src_feat* and *out_deg_feat* - on a diverse set of real-world temporal graphs. **TFCM_C** refers to the model variant using feature concatenation only.

7.1.1 Using only *src_feat*

Experiment for predicting the shortest temporal closeness using only the node feature *src_feat*.

Dataset	WKT (all nodes)	WKT (non zero)
mathoverflow	0.95	0.95
facebook	0.91	0.91
topology	0.81	0.81
mlwikiquote	0.98	0.98
plwikiquote	0.99	0.99
digg_reply	0.88	0.88
SMS	0.93	0.92
rt-pol	0.92	0.92
slashdot	0.86	0.85
wamazon	0.54	0.29
mgwikipedia	1.00	0.99
tgwiktionary	1.00	1.00
ltwiktionary	1.00	1.00

Table 14: Standard (all nodes) and filtered WKT scores for the **TFCM** (Temporal Fastest Closeness Model) (results of Table 13) - computed using the ordinal tie-breaking strategy. The filtered scores consider only nodes with non-zero ground truth values.

Dataset	Pred ≤ 0 , True > 0	SD	MAE
mathoverflow	9070	0	0.004
facebook	1890	0.006	0.053
topology	12304	0.061	0.063
mlwikiquote	371	0.020	0.006
plwikiquote	1086	0	0
digg_reply	18052	0.001	0.016
SMS	18576	0.011	0.008
rt-pol	4792	0	0.006
slashdot	44108	0.008	0.011
wamazon	23401	0.062	0.049
mgwikipedia	960	0	0
tgwiktionary	120	0	0
ltwiktionary	340	0	0

Table 15: The table reports (i) the number of nodes with predicted closeness values ≤ 0 while the ground truth closeness is > 0 , (ii) the Supremum Deviation (SD), and (iii) the Mean Absolute Error (MAE) for the **TFCM** (Temporal Fastest Closeness Model) across the testing datasets (results from Table 13).

Dataset	Top-1%	Top-5%	Top-10%	Top-20%	Jaccard
mathoverflow	0.00	0.13	0.34	0.30	0.59
facebook	0.00	0.01	0.05	0.23	0.75
topology	0.00	0.01	0.01	0.03	1.00
mlwikiquote	0.00	0.04	0.07	0.21	0.09
plwikiquote	0.04	0.18	0.28	0.31	0.16
digg_reply	0.01	0.06	0.14	0.31	0.57
SMS	0.00	0.02	0.05	0.15	0.39
rt-pol	0.01	0.04	0.08	0.22	0.19
slashdot	0.00	0.08	0.35	0.61	0.99
wamazon	0.03	0.06	0.21	0.54	1.00
mgwikipedia	0.00	0.02	0.03	0.19	0.00
tgwiktionary	0.00	0.05	0.11	0.21	0.00
ltwiktionary	0.01	0.04	0.11	0.14	0.00

Table 16: Top-N accuracy and Jaccard similarity for the **TFCM** (Temporal Fastest Closeness Model) – using only *src_feat* as a node feature – on a diverse set of real-world temporal graphs.

7.2 Temporal Shortest Closeness Model (TSHCM)

Integration of a new node feature: `out_reach_feat`. For the prediction of the temporal shortest closeness an additional scalar feature, namely `out_reach_feat`, is incorporated alongside the primary node feature `src_feat`.

`out_reach_feat`: It counts how many nodes are reachable from a node u via time-respecting paths of up to k hops. For $k = 2$, this includes temporal paths of length 1 or 2. Higher values mean u can reach many nodes through short temporal paths, though not necessarily the shortest possible ones.

Dataset	Top-1%	Top-5%	Top-10%	Top-20%	Jaccard
mathoverflow	0.87	0.78	0.73	0.70	1.00
facebook	0.52	0.55	0.60	0.67	1.00
topology	0.89	0.82	0.78	0.74	1.00
mlwikiquote	0.82	0.93	0.87	1.00	1.00
plwikiquote	0.81	0.99	0.92	0.97	1.00
digg_reply	0.50	0.61	0.68	0.76	1.00
SMS	0.67	0.63	0.67	0.88	1.00
rt-pol	0.66	0.74	0.81	0.97	1.00
slashdot	0.62	0.61	0.61	0.66	1.00
wamazon	0.82	0.60	0.84	0.70	1.00
mgwikipedia	1.00	0.91	0.96	0.97	1.00
tgwiktionary	1.00	0.91	0.97	0.97	1.00
ltwiktionary	1.00	1.00	1.00	1.00	1.00

Table 17: Top-N accuracy and Jaccard similarity for the **TSHCM** (Temporal Shortest Closeness Model), using *src_feat* and *out_deg_feat* - on a diverse set of real-world temporal graphs.

Dataset	WKT (all nodes)	WKT (non zero)
mathoverflow	0.93	0.89
facebook	0.90	0.88
topology	0.91	0.91
mlwikiquote	0.99	0.92
plwikiquote	0.99	0.93
digg_reply	0.93	0.90
SMS	0.95	0.91
rt-pol	0.97	0.92
slashdot	0.90	0.90
wamazon	0.90	0.90
mgwikipedia	1.00	0.93
tgwiktionary	1.00	0.95
ltwiktionary	1.00	1.00

Table 18: Standard (all nodes) and filtered WKT scores for the **TSHCM** (Temporal Shortest Closeness Model) (results of Table 17) - computed using the ordinal tie-breaking strategy. The filtered scores consider only nodes with non-zero ground truth values.

Dataset	Pred ≤ 0 , True > 0	SD	MAE
mathoverflow	2460	0.178	0.205
facebook	7469	0.097	0.083
topology	1500	0.255	0.304
mlwikiquote	330	0.004	0.004
plwikiquote	2474	0.002	0.003
digg_reply	7687	0.011	0.043
SMS	11612	0.031	0.027
rt-pol	2185	0.003	0.023
slashdot	20718	0.110	0.153
wamazon	22988	0.441	0.066
mgwikipedia	1262	0	0
tgwiktionary	145	0	0
ltwiktionary	210	0	0

Table 19: The table reports (i) the number of nodes with predicted closeness values ≤ 0 while the ground truth closeness is > 0 , (ii) the Supremum Deviation (SD), and (iii) the Mean Absolute Error (MAE) for the **TSHCM** (Temporal Shortest Closeness Model) across the testing datasets (results from Table 17).

Appendices

A Temporal Graphs

Definition 1 (Temporal Graph). *A directed temporal graph is an ordered tuple $G = (V, \mathcal{E}, \mathcal{T})$ where:*

- V is the set of nodes,
- $\mathcal{E} = \{(u, v, t) : u, v \in V \wedge u \neq v \wedge t \in \mathcal{T}\}$ is the set of directed temporal edges,
- T is the set of time instants ³ t in which at least one temporal edge is present in the network.

Let $n = |V|$, $M = |\mathcal{E}|$, and $T = |\mathcal{T}|$ denote the number of nodes, edges, and distinct time instants, respectively. Given a subset of nodes $U \subseteq V$, the induced temporal subgraph is defined as $\mathcal{G}[U] := (U, \mathcal{E}')$, where $\mathcal{E}' := \{(u, v, t) \in \mathcal{E} : u, v \in U\}$.

It is also possible to define the *underlying static graph*:

Definition 2 (Underlying Static Graph). *Given a temporal graph $\mathcal{G} = (V, \mathcal{E}, \mathcal{T})$, the underlying static graph is $G_{\mathcal{G}} = (V, E)$, where $E = \{(u, v) : \exists (u, v, t) \in \mathcal{E}\}$.*

The $G_{\mathcal{G}}$ is often a lossy representation of the network \mathcal{G} , since it ignores the timing of the events in the entire network.

A.0.1 Temporal Paths

Definition 3 (Temporal Path). *Given a temporal graph $G = (V, \mathcal{E}, \mathcal{T})$ and two nodes $s, z \in V$, a temporal path $tp_{sz} \subseteq V \times V \times T$ is a sequence of time-respecting temporal edges*

$$((u_1, u_2, t_1), (u_2, u_3, t_2), \dots, (u_{k-1}, u_k, t_{k-1}))$$

such that:

- $u_1 = s, u_k = z$,
- $t_i < t_{i+1}$ for all $1 \leq i < k - 1$,
- all nodes u_i are distinct.

This definition ensures that edge timings respect causality. The definition can be adapted to non-strict inequalities ($t_{i+1} \geq t_i$) as needed. A node v is said to be *internal* to tp_{sz} if it appears in a temporal edge and $v \notin \{s, z\}$.

³The value \mathcal{T} denotes the life-time of the temporal graph, and, without loss of generality for our purposes, we assume that, for any $t \in \mathcal{T}$, there exists at least one temporal arc at that time and without loss of generality we assume $\mathcal{T} = [1, |\mathcal{T}|]$.

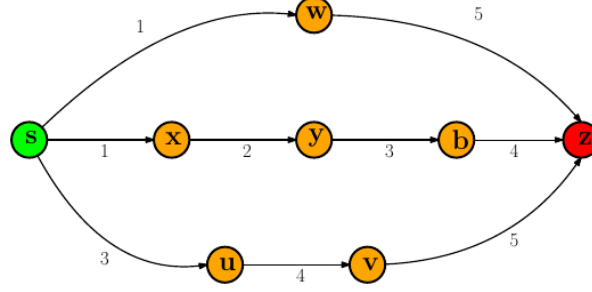


Figure 1: Example of the optimal-temporal paths: shortest, foremost and fastest

Definition 4 (Optimal Temporal Paths). Let tp_{sz} be a temporal path from s to z as above. Different optimality criteria are defined as follows:

- **Shortest (sh)**: minimizes the number of edges (hops) in the path.
- **Foremost (fm)**: arrives at z at the earliest possible time.
- **Fastest (fs)**: minimizes the total traversal time ($t_z - t_s$).
- **Shortest-Foremost (sfm)**: no other path arrives earlier and has fewer transitions.
- **Shortest-Fastest (sfs)**: no other path is faster and has fewer transitions.
- **Prefix-Foremost (pfm)**: is foremost and every prefix of the path is also foremost.

Figure 1 illustrates examples of the first three path types:

- $(s \xrightarrow{1} w \xrightarrow{5} z)$ is shortest,
- $(s \xrightarrow{1} x \xrightarrow{2} y \xrightarrow{3} b \xrightarrow{4} z)$ is foremost,
- $(s \xrightarrow{3} u \xrightarrow{4} v \xrightarrow{5} z)$ is fastest.

A.0.2 Temporal Betweenness Centrality

Just like in static graphs, centrality measures help identify important nodes. In temporal graphs, we focus on *temporal betweenness centrality*, which considers the number of optimal temporal paths a node participates.

Definition 5 (Temporal Betweenness Centrality). Given a temporal graph $\mathcal{G} = (V, \mathcal{E}, \mathcal{T})$ and a path optimality criterion (\star) , let:

- $\sigma_{sz}^{(\star)}$ be the number of (\star) -temporal paths from s to z ,
- $\sigma_{sz}^{(\star)}(v)$ be the number of such paths that pass through node v , with $s \neq v \neq z$.

Then, the **normalized (\star) -temporal betweenness centrality** of a node $v \in V$ is:

$$b_v^{(\star)} = \frac{1}{n(n-1)} \sum_{\substack{s, z \in V \\ s \neq v \neq z}} \frac{\sigma_{sz}^{(\star)}(v)}{\sigma_{sz}^{(\star)}} \in [0, 1].$$

Computing this measure is significantly more complex than in static graphs. For many criteria, it is known to be #P-Hard, so we focus on those variants for which polynomial-time algorithms exist.

A.1 Temporal Closeness

Definition 6 (Harmonic Temporal Closeness). *Using the optimal distance computations for earliest arrival paths, fastest paths, and other temporal metrics, we define four versions of harmonic temporal closeness for a node u as:*

$$C(u) = \sum_{\substack{v \in V \\ v \neq u}} \frac{1}{d(u, v)},$$

where $d(u, v)$ denotes the temporal distance from node u to node v under the chosen distance metric. By convention, we set $\frac{1}{\infty} = 0$ for non-reachable vertices.

B Further on FiLM Architecture

B.1 How FiLM Operates Over Features in the Model

Feature-wise Linear Modulation (FiLM) is a conditioning mechanism that adjusts neural network activations using external signals. In our model, FiLM modulates the primary node representation (`src_feat`) using a graph-theoretic input: the pass-through degree (`ptd_feat`), which measures how frequently a node mediates time-respecting paths.

Instead of processing `src_feat` and `ptd_feat` jointly, FiLM treats `ptd_feat` as a controller. It produces per-feature scaling and shifting parameters applied to `src_feat` via:

$$\text{modulated_feat} = \text{src_feat} \times \gamma(\text{ptd_feat}) + \beta(\text{ptd_feat}),$$

where γ and β are learnable projections of the scalar `ptd_feat` to match the dimension of `src_feat`.

This modulation is applied not just at the input, but throughout deeper MLP layers, allowing the model to adapt the importance of features at multiple transformation stages. Notably, `ptd_feat` itself is not transformed or modulated, preserving its role as a stable, interpretable conditioning signal.

Overall, FiLM enables dynamic reweighting of node features while maintaining the interpretability of the external signal. This leads to more expressive and targeted transformations of `src_feat`, especially valuable in capturing node importance in temporal graphs.

Example: tgwiktionary Dataset. This dataset contains 33,968 nodes, of which only 235 have non-zero temporal betweenness scores. We expect the model to:

- Predict high values for these top 235 nodes;
- Assign uniform low values to all others.

Under FiLM, the model outputs distinct scores for top nodes (e.g., 0.746, 0.551, 0.337), while collapsing all other predictions to a single low value (e.g., -1.41), clearly separating predictions from noise. By contrast, the concatenation-only model produces scattered negative values for irrelevant nodes (e.g., -0.25, -0.51, -0.29), reducing ranking sharpness. Evaluation results confirm this: FiLM achieves $\text{Top-1\%} = 1.0$, while concatenation yields $\text{Top-1\%} = 0.85$. (see Table 2)

B.2 When the `CF` variant Outperforms or Underperforms `C` variant

The combination of FiLM and concatenation performs variably depending on dataset characteristics:

- **In dense or structured graphs** (e.g., SMS, slashdot), the `CF` variant tends to outperform `C` variant because:
 - FiLM highlights attention-relevant dimensions guided by PTD;
 - Concatenation preserves an explicit, interpretable PTD input;
 - The two mechanisms complement each other: one reshapes internal representations, the other offers direct supervision.
- **In sparse or skewed graphs** (e.g., mathoverflow), `CF` variant may underperform:
 - FiLM modulation can distort already informative `src_feat` signals;
 - This can hurt top-1% accuracy, where relevant nodes are rare and highly concentrated.

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