Abstract—In this work, we study the information spreading time in multiplex networks, adopting the gossip (random-walk) based information spreading model. A new metric called multiplex conductance is defined based on the multiplex network structure and used to quantify the information spreading time in a general multiplex network in the idealized setting. Multiplex conductance is then evaluated for some interesting multiplex networks to facilitate understanding in this new area. Finally, the tradeoff between the information spreading efficiency improvement and the layer cost is examined to explain the user’s social behavior and motivate effective multiplex network designs.

I. INTRODUCTION

In the past election year, one of the most important tasks for presidential candidates is to disseminate their words and opinions to voters in a fast and effective manner. The underlying research problem on information spreading has already received great interest and been extensively studied in a single network. However, with the continuous advancement of modern technology, the ways that the candidates can exploit to promote their influence are no longer limited to the campaign tour; radio networks, TV networks, telephone networks, and Internet have all been utilized for their purposes. Especially, with the phenomenal popularity of social networks, all candidates have utilized their Facebook and Twitter accounts to post and spread their political agenda, through which their words can be shared and disseminated in an unprecedented range and scale. Therefore, with increasingly complicated interconnections and interactions, various kinds of communication networks and social media have formed a new network structure that enables people to spread and receive information simultaneously through multiple channels and platforms. Recently, multilayer network models have been introduced to facilitate relevant studies on emerging interconnected complex networks [1, 2]. In this work, we take a first step to investigate information spreading in a special type of multilayer networks, termed multiplex networks, for which all layers share the same set of nodes. In practice, the same set of nodes may correspond to individuals who can communicate through multiple networks or platforms, and duplicates of the same node may represent different communication devices or social accounts a person may have. Arguably, this somewhat simplified version of multilayer networks already captures many interesting multi-scale and multi-component features, and serves as a good starting point for our intended study.

There has been some works on information spreading in multiplex networks, which are based on the compartmental epidemic spreading models [3, 4], and mainly focus on the macroscopic network behavior. Our work instead adopts the gossip (random-walk) based information spreading model [5], which is considered as reflecting more details of the underlying communication dynamics and network structures, and can facilitate the quantification of the information spreading time. To the best of our knowledge, this information spreading model has not been explored for multiplex networks.

In this work, the gossip-based information spreading time is found to be closely connected to a newly defined metric multiplex conductance. Specifically, our contributions can be summarized as follows:

- A new metric, multiplex conductance $\Phi_{\text{mp}}$, is defined based on the multiplex network structure, and it is shown that $\Theta(\Phi_{\text{mp}}^{-1} \cdot \log n)$ is a good estimate for information spreading time in many multiplex networks of interest.
- Multiplex conductance of some interesting multiplex networks is evaluated to shed light on this burgeoning research field.
- The tradeoff between the cost of additional layers and the improvement of information spreading efficiency is discussed from both the user’s and the network designer’s aspect.

The rest of the paper is organized as follows. The system model and gossip algorithm for multiplex networks are introduced in Section II. Section III presents the main theoretical results for information spreading time in multiplex networks and the evaluation of multiplex conductance. In Section IV, some discussion on the trade-off between the layer cost and the improvement of information spreading efficiency is given. Section V concludes the work.

II. PROBLEM FORMULATION

In this section we briefly introduce the network and system models. More details can be found in the technical report [6].

A. Basic Models

1) Multiplex Network: A multilayer network is modeled by a family of graphs $\{G_m \triangleq (V_m, E_m)\}_{m=1}^{M}$ that constitute the
layers of this complex system, together with the interlayer connections represented by $E_{\alpha\beta}$, for any two different layers $G_\alpha$ and $G_\beta$. In this study, we will focus on multiplex networks, for which all layers share the same set of nodes, i.e., $V_1 = V_2 = \ldots = V = [n]$, and interlayer connections exist only between the duplicates of the same node at different layers, i.e., $E_{\alpha\beta} = \{(v_\alpha, v_\beta); v \in V\}$ for all $\alpha \neq \beta$, where $v_\alpha$ is the duplicate of node $v$ in layer $\alpha$.

2) Synchronous Time Model: In this work, the synchronous time model is adopted, i.e., all nodes in the network take action simultaneously at discrete time steps. This is a common model used for studying gossip-based information spreading [8].

3) Gossip Algorithm in Multiplex Network: For the gossip algorithm in the single network, in each time slot, each node contacts one of its neighbors independently and uniformly at random. The push-pull model is considered for transmitting information. Specifically, in each round, for the push operation, every informed node randomly chooses a neighbor and attempts to pass the information, while for the pull operation, every uninformed node randomly chooses a neighbor and attempts to grab the information. In this work, we will consider the following gossip algorithm for a multiplex network: Before the gossip process, it is assumed that all duplicates of the same node are synchronized. During a gossip step, all nodes and their duplicates contact one of their neighbors uniformly at random in all layers simultaneously. After each gossip step, the newly informed nodes (if they exist) will broadcast the information to all their duplicates.

B. Information Spreading Time

The metric commonly used to measure the efficiency of gossip based information spreading is the information spreading time. Denote $S_t$ as the informed node set at round $t$, with $S_0 = \{s\}$, for some arbitrary $s \in V$. The information spreading time in a network $G$ of size $n$, $T_{spr}(G, \gamma), \gamma > 0$, is modeled as the stopping time by which all nodes are informed with probability $1 - O(n^{-\gamma})$ [8], i.e., $T_{spr}(G, \gamma) = \sup \inf \{t : Pr(S_t \neq V | S_0 = \{s\}) \leq O(n^{-\gamma})\}$.

III. MAIN RESULTS

For the gossip model, analyzing the information spreading process is difficult even in a single network due to the heterogeneous network topology and random gossip processes. The multiplex network structure introduces interconnections and interactions among layers, which further complicate the analysis. In this study, we slightly relax the problem and endeavor to find the information spreading time in a general multiplex network in an idealized setting.

First, the following definition is needed for the following analysis:

Definition 1: Given a multiplex network $G = \{G_m \triangleq (V, E_m)\}_{m=1}^M$, for each node $u \in V$, $d_m(u)$ is defined as the node degree of $u$ in layer $m$. The maximum total node degree is then defined as $\Delta_{\text{max}} = \max_{u \in V} \left(\sum_{m=1}^M d_m(u)\right)$. The total neighbor set $\text{Neg}(u)$ of node $u$ is defined as the set of all unique nodes connected to $u$ in any layer, i.e., $v \in \text{Neg}(u)$ if $(u, v) \in \bigcup_{m=1}^M E_m$. If $v \in \text{Neg}(u)$, the link $(u, v)$’s existing layer set is defined as $L_{(u,v)} = \{\alpha; (u, v) \in E_\alpha\}$, and the corresponding $(u, v)$ link at layer $\alpha$ is denoted as $(u, v)_\alpha$.

A. Idealized Information Spreading Time

The analysis for information spreading in the multiplex network is mainly complicated by two factors: overlapping edges among layers and heterogeneous contacting probabilities at different layers. They render the exact estimation of information spreading time in the multiplex network intractable. Therefore, an idealized setting is considered in the following so that the corresponding information spreading time can be analyzed, which serves as a good lower bound for the information spreading time of the original multiplex network. First, to handle the overlapping edges among layers, an aggregated multigraph representation for a multiplex network is constructed as follows:

Definition 2: Given a multiplex network $G = \{G_m \triangleq (V, E_m)\}_{m=1}^M$, the corresponding aggregated multigraph $\tilde{G} = (\tilde{V}, \tilde{E})$ is defined such that $\tilde{V} = V$ and $\tilde{E} = \bigcup_{m=1}^M E_m \triangleq \{(u, v)_\alpha; u \in V, v \in \text{Neg}(u), \alpha \in L_{(u,v)}\}$, where $\cup$ stands for the non-unique set union, i.e., the same links at different layers are all kept.

To get around heterogeneous at different layers, node $u$’s contacting probability for each link $(u, v)_\alpha$ is unified as $\mathcal{P}(u) = \mathbb{P}(u, v)_\alpha = \frac{1}{\min_{m \in \{1, \ldots, M\}} d_m(u)}$ (denoted as link picking probability). This over-optimistic choice simplifies our analysis, while still providing a good lower bound as shown below.

The idealized setting is formed through a uniform gossip with link picking probability $\mathcal{P}(u), \forall u \in V$, on the aggregated multigraph $\tilde{G}$ constructed above. The information spreading time in this idealized setting for an arbitrary multiplex network is quantified below.

Definition 3: The multiplex conductance $\Phi_{\text{mp}}$ of a multiplex network $\{G_m \triangleq (V, E_m)\}_{m=1}^M$ is defined as

$$\Phi_{\text{mp}} = \min_{S \subseteq V, \text{vol}_{\text{T}}(S) \leq |E|_{T}} \frac{M |\text{cut}_{T}(S, V - S)|}{\text{vol}_{T}(S)},$$

where $\text{vol}_{T}(S) = \sum_{m=1}^M \text{vol}_{m}(S)$, $|E|_{T} = \sum_{m=1}^M |E_m|$, and $|\text{cut}_{T}(S, V - S)| = \sum_{m=1}^M |\text{cut}_{m}(S, V - S)|$, $\text{vol}_{m}(S)$ is the degree sum of all nodes in the node set $S$ at layer $m$ (volume), and $|\text{cut}_{m}(S, V - S)|$ is the number of edges between node set $S$ and $V - S$ at layer $m$.

Theorem 1: For an $M$-layer multiplex network with $n$ nodes, the information spreading time in the idealized setting is at most $200(\gamma + 2)\Phi_{\text{mp}}^{-1} (\log n + \frac{1}{2} \log M)$ rounds with probability $n$. \footnote{Link $(u, v)$ may exist in several layers simultaneously. \footnote{Note that multiple edges are allowed between a pair of nodes in a multigraph.}
with probability at least \(1 - O(n^{-\gamma})\), where \(\Phi_{mp}\) is the multiplex conductance of this multiplex network.

First, the following sequence of random variables solely related to the pull operation will be introduced to facilitate our analysis. Let \(L_1, L_2, \ldots\) be a sequence of random variables with \(L_i \geq 1\) defined as follows: We distinguish two cases:

- If \(vol_T(S_{i-1}) \leq |E|_T\), then by Definition 3, \(\Phi_{mp}vol_T(S_{i-1}) \geq \frac{1}{\gamma} \Phi_{mp}vol_T(S_0)\), where \(U_{i-1} = V - S_{i-1}\) is the set of uninformned nodes at round \(i - 1\). Let \(R = [\Phi_{mp}vol_T(S_0)]\) and \(E_i\) be an arbitrary subset of \(\cup_{m=1}^{M} c u t_m(S_{i-1}, U_{i-1})\) consisting of \(\frac{1}{\gamma} R\) edges. Set \(E_i\) is (arbitrarily) fixed at the beginning of round \(i\) before the round is executed. Define the minimum volume of a node \(u\) as \(M \cdot \min_m \{d_m(u)\}\). For each node \(u \in U_{i-1}\), let \(\sigma(u)\) be a 0/1 random variable with \(\sigma(u) = 1\) if and only if in round \(i\) node \(u\) pulls the information through some edge in \(E_i\). Then, \(L_i = \sum_{u \in U_{i-1}} |\sigma(u)| M \cdot \min_m \{d_m(u)\}\).

- If \(vol_T(S_{i-1}) > |E|_T\), then \(L_i = R\).

Then, the following two lemmas are proved to show

**Theorem 1:**

**Lemma 1:**

(a) \(E(\sum_{k \leq L_k} = iR \text{ and } Var(\sum_{k \leq L_k} \leq iR\Delta_{max}, \text{where } R = [\Phi_{mp}vol_T(S_0)] \).\)

(b) \(\text{vol}_T(S_0) < \Delta_{max}\), then \(\Pr(\text{vol}_T(S_i) > \Delta_{max}) \geq 1/2\), for \(i \geq 4\Phi_{mp}/\Phi_{mp}vol_T(S_0)\).

(c) \(\Delta_{max} \leq \text{vol}_T(S_0) \leq |E|_T\), then \(\Pr(\text{vol}_T(S_i) \geq \min(2\text{vol}_T(S_0), |E|_T + 1)) \geq 1/2\), for \(i \geq 4/\Phi_{mp}\).

(d) \(\text{vol}_T(S_0) > \text{vol}_T(U_0) \geq |E|_T\), then \(\Pr(\text{vol}_T(U_i) \leq \text{vol}_T(U_0)/2) \geq 1/2\), for \(i \geq 6/\Phi_{mp}\), where \(U_i = V - S_i\) is the set of uninformned nodes at round \(i\).

**Lemma 2:** \((\delta)\) Let \(\varepsilon_{PUSH}(a, b, t)\) denote the event that the pull operation spreads to node \(b\) the information started at node \(a\) in at most \(t\) rounds; and \(\varepsilon_{PULL}(a, t)\) denote the event that the pull operation spreads to node \(a\) the information started at node \(b\) in at most \(t\) rounds. Then \(\Pr(\varepsilon_{PUSH}(a, b, t)) = \Pr(\varepsilon_{PULL}(b, a, t))\).

**Remark 1:** The random variables \(L_i\) are used to approximate the increment of \(\text{vol}_T(S_i)\). With the expectation and variance of the sum of random variables \(L_i\) in Lemma 1(a), different increasing speeds of \(\text{vol}_T(S_i)\) are shown in Lemma 1(b), (c), and (d) for three different stages. (d) actually shows the decreasing speed of its complement \(\text{vol}_T(U_i)\). Lemma 2 shows the symmetry between the pull and push operation. The proof of Lemma 1 (and more details for that of Theorem 1) can be found in [6].

**Sketch of Proof for Theorem 1:** When only the pull operation is considered, it can be seen from Lemma 1 that the total volume of the informed node set \(\text{vol}_T(S_i)\) increases in different ways in the three different stages. The information spreading analysis is given below accordingly. In the first stage, by Lemma 1(b), if given \(\text{vol}_T(S_0) < \Delta_{max}\), after at most \(5\Delta_{max}/(\Phi_{mp}vol_T(S_0))\) rounds, the total volume of the informed node set becomes at least \(\Delta_{max}\) with probability at least \(1/2\). Now, divide the information spreading process in this stage into phases each comprised of \(5\Delta_{max}/(\Phi_{mp}vol_T(S_0))\) rounds. A phase is considered successful if the total volume of the informed node set at the end of that phase is at least \(\Delta_{max}\). Therefore, in the first \(2\gamma \ln n\) phases, the probability that none of them is successful is at most \((1 - 1/2)^{2\gamma \ln n} \leq O(n^{-\gamma})\). Therefore, with at most \(t = 3\gamma \ln n \cdot 5\Delta_{max}/(\Phi_{mp}vol_T(S_0))\) rounds, the total volume of the informed node set has \(\text{vol}_T(S_i) \geq \Delta_{max}\) with probability at least \(1 - O(n^{-\gamma})\).

In the second stage, by Lemma 1(c), if \(\Delta_{max} \leq \text{vol}_T(S_0) \leq |E|_T\), then with probability at least \(1/2\), it takes at most \(4/\Phi_{mp}\) rounds until the total volume of the informed node set is increased to at least \(\min(2\text{vol}_T(S_0), |E|_T + 1)\). Similarly, divide the information spreading process in this stage into phases each \(4/\Phi_{mp}\) rounds each. A phase is successful if the total volume of the informed node set at the end of the phase is at least \(\min(2\text{vol}_T(S_0), |E|_T + 1)\), where \(S_i\) is the set of informed nodes at the beginning of that phase. Then, for any \(k\), the probability that the \(k\)-th phase is successful is at least \(1/2\), regardless of the outcome of the previous \(k - 1\) phases. Let \(B(k, 1/2)\) denote the binomial random variable for \(k\) trials each with success probability of \(1/2\). Then, by the Chernoff bound, the probability that fewer than \(\eta = \log |E|_T\) of the \((2\gamma + 4)\eta\) phases are successful is at most \(\Pr(B(k, 1/2) \leq \eta) \leq e^{-(\eta - k^2)/2k} \leq O(n^{-\gamma})\), since \(|E|_T = n - 1\). And since at most \(\eta\) successful phases are required for the total volume of the informed node set exceeding \(|E|_T\), it follows that with probability \(1 - O(n^{-\gamma})\) the number of rounds required for the same goal is at most \(k \cdot 5/\Phi_{mp} \leq (2\gamma + 4)(2\log n + \log M)/(5/\Phi_{mp})\) as \(|E|_T \leq M \cdot n^2\).

Finally, by Lemma 1(d), if \(\text{vol}_T(S_i) > |E|_T\), by similar reasoning as before, we can show that once the total volume of informed nodes has exceeded \(|E|_T\), then \((2\gamma + 4)(2\log n + \log M)/(5/\Phi_{mp})\) rounds suffice to inform all nodes with probability \(1 - O(n^{-\gamma})\).

Combining the above three cases and applying the union bound, we obtain that, with probability \(1 - O(n^{-\gamma})\), all nodes get informed within \(50(\gamma + 2)(\log n + \log M)/(\Phi_{mp} + \Delta_{max}/(\Phi_{mp}vol_T(S_0)))\) rounds given any initial informed node set \(S_0\) when only the pull operation is considered.

Then let \(v_{max}\) be the node of maximum total node degree \(\Delta_{max}\) (see Definition 1). From above, the pull operation distributes the information from \(v_{max}\) to any other nodes in \(100(\gamma + 2)(\Phi_{mp}^{-1} \cdot (\log n + \frac{1}{2} \log M))\) rounds w.h.p. Then by Lemma 2, the push operation can spread to \(v_{max}\) the information started at an arbitrary source node \(s\) in \(100(\gamma + 2)(\Phi_{mp}^{-1} \cdot (\log n + \frac{1}{2} \log M))\) rounds with the same high probability. Therefore, the push-pull operation can spread the information started at \(s\) to all nodes in \(200(\gamma + 2)(\Phi_{mp}^{-1} \cdot (\log n + \frac{1}{2} \log M))\) rounds w.h.p.

**Remark 2:** By Theorem 1, we have shown that \(\Theta(\Phi_{mp}^{-1} \cdot \log n)\) is a good estimate for information spreading time in a general multiplex network in the idealized setting. It becomes a true lower bound for the actual information spreading time when the layer number of multiplex networks is sufficiently
large, as shown below.

**Theorem 2:** Given an $M$-layer multiplex network $G = \{G_m\}_{m=1}^M$ with $n$ nodes, there always exists a constant $c_n > 0$ such that, when $M > c_n$, $\Theta(\Phi^{-1}_{\text{mp}} \cdot \log n)$ is a lower bound of the actual information spreading time.

**Proof:** See [6].

While Theorem 2 is interesting in theory, in practice, $M$ is often a modest number. In this case, if it can be further shown that the information spreading capability of each layer is accurately measured (in the order sense) by the corresponding conductance, $\Theta(\Phi^{-1}_{\text{mp}} \cdot \log n)$ can still be a good lower bound for the actual information spreading time of a multiplex network. More discussions can be found in [6]. For single networks, many graph models of interest actually satisfy this property. Prominent examples include complete graphs, ring graphs, random geometric graphs (RGGs), and expander graphs (which include Preferential Attachment (PA) graphs as a special case). In this case, the maximum improvement of information spreading efficiency from a single network with conductance $\Phi$ to a multiplex network with multiplex conductance $\Phi_{\text{mp}}$ can be orderly determined by $P_I = \frac{\Phi}{\Phi_{\text{mp}}}$. A common misconception that the best achievable improvement for information spreading in a multiplex network formed with similar-topology layers would be on the order of $M$. Our first example below dispels this misconception through an innovative design exploiting the second factor above.

1) **Proposed Ring-Ring Multiplex Network:** In this example, a novel ring-ring multiplex network structure is proposed to demonstrate the impact of increased contacting opportunities in a multiplex network, for which an improvement as large as $\Theta(\sqrt{n})$ can be achieved, as shown in Fig. 1. In this proposed multiplex network structure, the first layer is a normal ring, where nodes are identified with the integers $1, 2, ..., n$. Assuming without loss of generality that $n + 1$ is not a prime number, find out its factor $r$ that is closest to $\sqrt{n}$. Then in the second layer, node with ID $i$ is connected to two nodes with IDs $((i+r) \mod n)$ and $((i-r) \mod n)$ instead (see Fig. 10 in [6] for details). It can be shown that the second layer is guaranteed with a ring structure. Then the multiplex conductance of this network structure is given by $\Phi_{\text{mp}} = 2 \min \{r+1, (n+1)/r+1\}$. Detailed calculation can be found in [6]. As shown in Fig. 1, the predicted information spreading efficiency improvement $P_I = \frac{\Phi}{\Phi_{\text{mp}}} = \min\{r + 1, \frac{n + 1}{r} + 1\}$ is quite tight in this scenario.

**Remark 3:** The second layer of the proposed ring-ring structure dramatically increases the size of cut through rewiring of nodes without increasing the corresponding set volumes. This design leads to an information spreading efficiency improvement on the order of $\min\{r + 1, (n+1)/r+1\}$, which is close to $\sqrt{n}$ in most cases.

2) **Different-Topology Multiplex Network:** This example reveals increased contacting opportunities in a multiplex network from a new perspective. Note that multiplex networks don’t need to be constrained to constructions of similar-topology layers. Intuitively, a marriage of different topologies can lead to a dramatic improvement in information spreading for the disadvantaged layer, as shown by the following two cases.

- **Ring-Complete Coupling:** If a ring graph is coupled with another complete graph to form a ring-complete

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**Fig. 1:** Proposed Ring-Ring

**Fig. 2:** Ring-Complete, PA

**Fig. 3:** Information Spreading in Multiplex Networks with Identical Ring Graphs
3) Identical-Topology Multiplex Network: Finally, the impact of layer number $M$ is explored, considering a special type of multiplex networks formed with $M$ layers of identical topology. When $M$ identical graphs having conductance $\Phi$ form a multiplex network, the overall multiplex conductance can be shown as $\Phi_{mp} = M\Phi$. Therefore, an improvement of order $M$ is expected for information spreading efficiency in this setting, which is generally an over-estimate, as the effect of link collision at different layers is ignored. This effect is most severe for the identical-layer structure, and can be partially corrected by considering the average meaningful contact for each node, which is upper bounded by $\Delta(1 - (1 - \frac{1}{\Delta})^M)$, where $\Delta$ is the largest degree of each layer. This simple correction leads to an improvement as shown in Fig. 2. For multiplex networks constructed by independent layers, the over-estimation error is usually not a concern.

IV. LAYER COST AND INFORMATION SPREADING EFFICIENCY

In real life, the adoption of a new layer comes with an additional cost. In this section, the tradeoff between the improvement of information spreading efficiency and the additional layer cost is discussed. In particular, we will exam two types of cost below:

• Network Cost for a User: The cost of additional layers from a user $u$’s aspect is measured by the total degree of this node in all layers, i.e., $C_{ML}(u) = \sum_{m=1}^{M} d_m(u)$. Therefore, the corresponding cost increase for the user $u$ is $C_{1,U}(u) = \sum_{m=1}^{M} \frac{d_m(u)}{d(u)}$, where $d(u)$ is the node degree of $u$ in the initial single network.

• Network Cost for the Network Designer: Different from the user’s aspect, for a network designer, the cost of a new layer is better measured by the number of total edges of it. Then the cost increase for the network designer is $C_{1,N} = \sum_{m=1}^{M} \frac{|E_n|}{|E|}$, where $|E|$ is the number of total edges of the initial single network.

With the cost increase $C_1$ for each multiplex network, and the corresponding information spreading efficiency improvement $P_1$, the reward-cost ratio can be defined as $RC = \frac{P_1}{C_1}$. In Table I, given an initial single ring graph, tradeoffs between the performance improvement and the cost are evaluated for four related multiplex networks.

<table>
<thead>
<tr>
<th>User</th>
<th>Network Designer</th>
<th>Proposed Ring-Ring</th>
</tr>
</thead>
<tbody>
<tr>
<td>Two-Identical-Ring</td>
<td>Ring-Complete</td>
<td>Ring-PA</td>
</tr>
<tr>
<td>$\Theta(1)$</td>
<td>$\Theta(1)$</td>
<td>$\Theta(n)$</td>
</tr>
</tbody>
</table>

Remark 4: From the results in Table I, it can be seen that overall the ring-PA coupling is the most effective multiplex structure as far as information spreading is concerned. Since the PA graph is a popular model for social platforms, this result partially reveals the beneficial impact of utilizing social networks for information distribution.

V. CONCLUSION AND FUTURE WORK

In this work, the gossip based information spreading is studied in multiplex networks. By defining the new metric multiplex conductance $\Phi_{mp}$, $\Theta(\Phi_{mp}^{-1} \cdot \log n)$ is found to be a good estimate for information spreading in many multiplex networks of interest. The multiplex conductance is then evaluated for several interesting multiplex networks to help understand information spreading potentials of multiplex networks. By further taking the additional layer cost into consideration, the tradeoff between the cost and the information spreading efficiency improvement is discussed from both the user’s and the network designer’s perspective to facilitate the understanding in this burgeoning area.

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The choices of cost in this paper mainly serve to facilitate relevant discussion. In practice, other meaningful costs may also be considered.

A single ring graph may serve as a coarse representation of a highly localized network, severely limited in information spreading capability.