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Tracing the Footsteps of Ideas: Time-respecting Paths Reveal Key Reformers and Communication Pathways in Protestant Letter Networks

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Abstract

The transmission of ideas plays a vital role in shaping society, fostering critical thinking, driving innovation, and facilitating cultural development. Previous studies have predominantly employed aggregated networks to investigate how ideas propagate through interactions and relationships among individuals. However, these approaches overlook the temporal ordering of interactions, distorting topological network measures and potentially leading to erroneous conclusions about idea transmission. To address this limitation, this study explores the transmission of ideas using time-respecting paths. A time-respecting path is defined as a sequence of nodes connected by time-consecutive edges, where the inter-edge time is constrained within specific bounds representing the minimum reaction time and maximum memory period before ideas fade away. By constructing time-respecting paths from a network of letter correspondences among 16th-century protestant reformers, this research unveils key reformers and communication patterns that significantly influenced the transmission of ideas. The findings are interpreted in the light of case studies, such as the Osiandrian controversy, which provides valuable insights into historical contexts.

Keywords: Temporal network analysis , European Reformation, transmission of ideas, time-respecting paths, letter correspondence network

1 Introduction

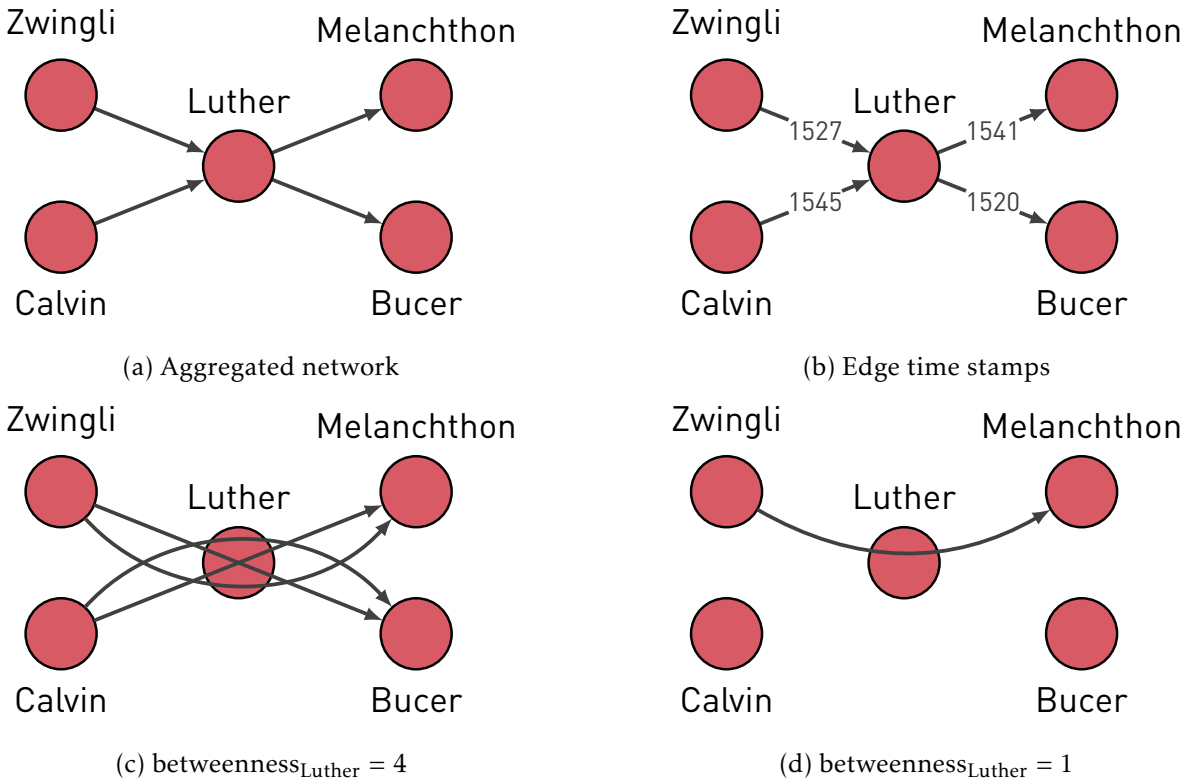
In 1571, protestant reformer Johannes Pappus introduced a new idea in a letter: Lutherans and Zwinglian-Reformed should unify despite their ideological differences (Pappus 1571). While groundbreaking for European unity (Treu 1999), Pappus should not be credited for the idea: He had simply copied it from reformer Jakob Andrea (Andreae 2023b; Andreae 2023a). This example illustrates the importance of understanding idea transmission in grasping reformers' historical roles.

However, the above example represents an exception in the study of idea transmission: Most data about 16th-century communication do not overtly reveal where ideas originated and who contributed to their transmission. Often, not even the letter texts are available and one only knows *that* two individuals exchanged a letter at a certain point in time but not *what* they wrote to each other. How can one still leverage these data to trace the flow of ideas in order to (1) identify important spreaders of knowledge among 16th-century protestant reformers and (2) explain the driving factors behind their prevalent communication patterns?

A popular approach is to construct a communication network from letter correspondences and use node betweenness centrality (Freeman 1978) to identify the important spreaders of ideas (R. Ahnert and S. E. Ahnert 2015; Borgatti 2005). In this communication network, nodes and edges correspond to individuals and their exchanged letters, respectively. The betweenness centrality of a node i counts the number of shortest connections that link any two node pairs and run via node i. In a communication network, i's betweenness is interpreted as the amount of information i passes on from one node to another. This interpretation only works because one assumes an incoming letter to induce an outgoing letter on the same topic, e.g., in the form of a reply or to pass on an idea to others (Petrovi, Wegner and Scholtes 2023). As a consequence, the chronological ordering of letters has to be preserved: The incoming letter has to be received before the outgoing letter is sent.

However, in aggregated networks the above assumption is violated. Since time is ignored the chronological ordering of edges may be broken which biases betweenness centrality (Scholtes, Wider and Garas 2016). Figure 1a visualizes this problem with letter exchanges between five protestant reformers in an aggregated network. If one ignores time and computes the betweenness centrality of Luther one sees that Luther connects all other four node pairs via shortest connections (Fig.1c). His betweenness is four. In contrast, if one considers time by including the sending dates of letters as edge time stamps (Fig. 1b) Luther only connects one node pair: Zwingli and Melanchthon. For the other node pairs, Luther sends his outgoing letters before receiving the incoming ones, and hence, cannot pass on ideas. Luther's betweenness decreases to one (Fig. 1d) This example shows that, in the aggregated network, connections mediated by Luther can run backwards in time, which overestimates Luther's role in the transmission of ideas.

Previous research has proposed a variety of methods to incorporate time in networks (Holme and Saramäki 2012; Holme 2015; Williams et al. 2022; P. Peixoto and Gauvin 2018). Among the most popular approaches, especially in historical network research, is the temporal snapshot approach. It splits the observation period into time slices and aggregates the nodes and edges inside each time slice into subnetworks. The main challenge is to choose the size of the time slices, and approaches range from pure data-



(a) Aggregated network

(b) Edge time stamps

(c) $\text{betweenness}_{\text{Luther}} = 4$

(d) $\text{betweenness}_{\text{Luther}} = 1$

Figure 1: Betweenness scores differ when computed on the aggregated network (a, c) and when accounting for time-stamped edges (b, d).

driven (Caceres and Berger-Wolf 2013; Darst et al. 2016; P. Peixoto and Gauvin 2018) to theory-driven ones (Lemercier 2015).

In historical network research, time slices correspond to diverse categories including Chinese dynasties (Bingenheimer 2021), periodizations of global intellectual knowledge (Petz, Ghawi and Pfeffer 2020), decisive moments in the planning of Hitler's assassination (Conroy et al. 2022) and movements helping Jews to hide in World War II (Düring et al. 2011), the smallest temporal unit in the data (e.g., years) (Gilles 2020; Buch-Hansen and Larsen 2021), and periods based on informed reasoning (D'haeninck, Nico and Verbruggen 2015) as well as periods that facilitate visualization (Van Vugt 2017). However, since subnetworks are aggregated the snapshot approach has the same problem as the global aggregated network: The temporal ordering of edges is not preserved allowing causal relations to run backwards in time.

In this article, I address this problem by analyzing time-respecting paths in a letter correspondence network of protestant reformers. A time-respecting path is a sequence of nodes that are connected by time-consecutive edges (e.g., Zwingli $\xrightarrow{1527}$ Luther $\xrightarrow{1541}$ Melanchthon in Figure 1d) with the inter-edge time being being bounded, i.e., the passed time between two consecutive edges must neither be too small nor too large. I use betweenness centrality to identify reformers who facilitated the transmission of ideas in the network and path length frequencies to identify dominant communication

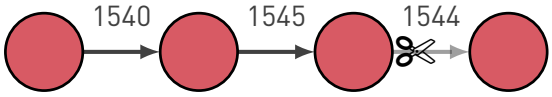
patterns. Results identify Philipp Melanchthon to be the most influential reformer for the spread of ideas and mediating as the most dominant communication pattern, i.e., communication via paths of length two. I use case studies of exemplary paths of length two to provide potential explanation for why mediating dominates.

To the best of my knowledge, this study is the first to apply time-respecting paths to network analyses of historical data. It addresses problems of standard temporal network approaches such as the temporal snapshot approach and contributes to the overall question of how to account for temporal information in quantitative historiographical research.

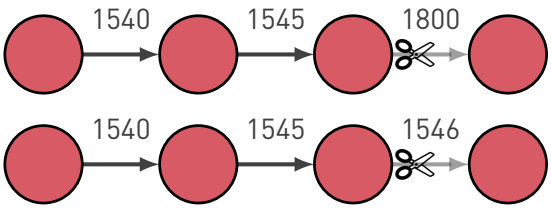
2 Background

This analysis is based on two main assumptions about communication networks. First, I assume an incoming message to induce an outgoing message on the same topic, and second I assume the outgoing message to be sent within a certain time window reflecting the minimal reaction time and memory of the recipient (Petrovi, Wegner and Scholtes 2023). Applied to the letter correspondence network of 16th-century reformers this means that if reformers A sends a letter to reformer B, B passes on A's ideas in their next letter if they have sufficient time to write that letter (minimal reaction time) and if they write it before forgetting about A's ideas (memory).

These assumptions are captured in time-respecting paths which I extract from the letter correspondence network of reformers. A time-respecting path is a sequence of nodes that are connected by time-consecutive edges (chronology) with the inter-edge time being restricted by a lower (minimal reaction time) and upper bound (memory) (Pfitzner et al. 2013). For example, the connection Zwingli $\xrightarrow{1527}$ Luther $\xrightarrow{1541}$ Melanchthon in Figure 1d represents a time-respecting path if ideas from Zwingli's letter in 1527 have not been forgotten by 1541, so Luther can pass them on in his letter to Melanchthon. Figure 2 shows that time-respecting paths are broken if either the edge



(a) Edge chronology is preserved



(b) Inter-edge time is bounded. Top/bottom: Too much/little time passes between two consecutive edges, respectively.

Figure 2: Properties of time-respecting paths.

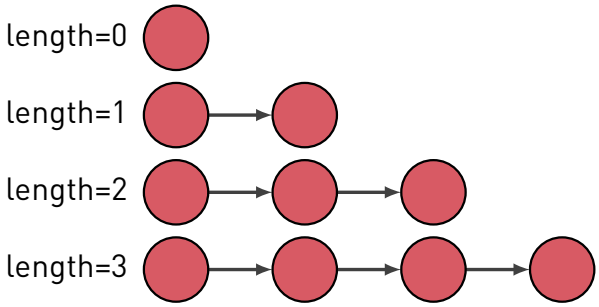
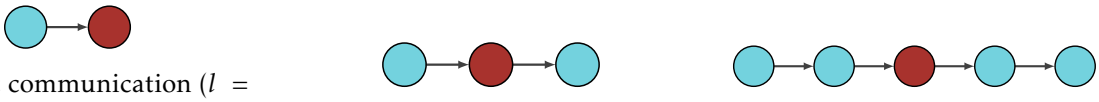


Figure 3: The length of a time-respecting path corresponds to the number of edges connecting the sequence of nodes. Path lengths are analyzed to identify dominant communication patterns.



(a) Diadic communication ($l = 1$)

(b) Mediating ($l = 2$)

(c) Chain linking ($l > 2$)

Figure 4: Communication patterns based on path length (l).

chronology is not preserved or too little/much time passes between two consecutive edges.

Time-respecting paths are useful because they improve centrality measures compared to aggregated networks (see Figures 1 and Scholtes, Wider and Garas (2016)). Since the temporal ordering of edges is not preserved in aggregated networks time can flow backwards on paths which overestimates centrality measures and makes reformers seem more influential for the transmission of ideas than they in fact were. Moreover, one can use the length of time-respecting paths, i.e., the number of edges connecting the sequence of nodes (Fig. 3), to gain insights into prevalent forms of communication such as diadic communication, mediating and chain linking (Fig. 4).

Whereas extracting chronological edges from a communication network is straightforward, choosing the correct inter-edge time to account for reaction time and memory is not. The timescale at which temporal edges influence each other is unknown (Petrovi, Wegner and Scholtes 2023), i.e., whether reformers pass on ideas from letters that they received five days, five month or five years ago. Moreover, the substantive travel times

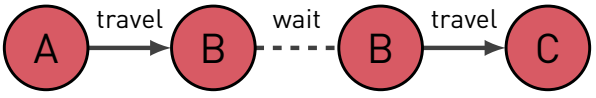


Figure 5: Temporal information in the letter correspondence network is split into travel and waiting times. Travel time refers to the duration between the date a letter is sent and the date it is received by the intended recipient. Waiting time refers to the duration between the date a letter is received by a recipient and the date they send out a new letter in response to the first one.

of letters affect the relevant timescale since recipients cannot forget ideas while the message is traveling, i.e., before it has reached the recipient. The receiver's memory is only active between the time they receive the message and the time when they send out a new one, a period I call 'waiting time' (Fig 5). Since my data only include the sending dates of letters but not the receiving dates, I have to estimate the latter and the consequent waiting times to compute time-respecting paths.

3 Methods

3.1 From Data to Temporal Network

I construct a temporal network from the letter editions of nine protestant reformers[1] (Bullinger 1974–2019; Zwingli 1905–2013; Kaufmann, T. (ed.) 2012; Luther 1883; Melanchthon 1977–2021; Myconius 2017; Bucer 1979–2016; Burnett 2019) with the python package `pathpy` (Scholtes 2022). Nodes correspond to reformers, edges to the exchanged letters, and edge time stamps to the letters' sending dates. Since `pathpy` requires unix time-stamps which do not cover dates before 1st January 1970, I translate sending dates for each edge e into a time difference: earliest sending date - sending date of e [days], where the earliest sending date in the data corresponds to 1st January 1500.

3.2 Extracting Time-respecting Paths

I extract time-respecting paths from the temporal network with `pathpy`. This step requires me to specify the upper bound of inter-edge times δt, corresponding to human memory. For the letter correspondence data, δt represents the maximum time allowed to pass between the sending dates of two consecutive letters in a time-respecting path.

I choose $\delta t = 15$ days because most letters were given to walking travelers who usually reached towns in the Holy Roman Empire within half a month, and reformers were diligent letter writers who replied quickly after having received a letter. Despite this informed reasoning, I acknowledge that my parameter choice is arbitrary and therefore perform robustness checks to see how this choice affects the results (see Section 2 in Supplementary Material). Moreover, I explore two approaches to estimate δt from the letter correspondence data, which were both unsuccessful due to missing data (see Section 1 in Supplementary Material). The lower bound of inter-edge times, i.e., the

[1] The letter editions of Bullinger and Melanchthon are work in progress and therefore not complete. Official letter editions of Vadian and Oekolampad do not exist and the letter used in this analysis are based on collections by Burnett (2019).

minimum reaction time, is set to one day since pathpy does not allow this parameter to vary.

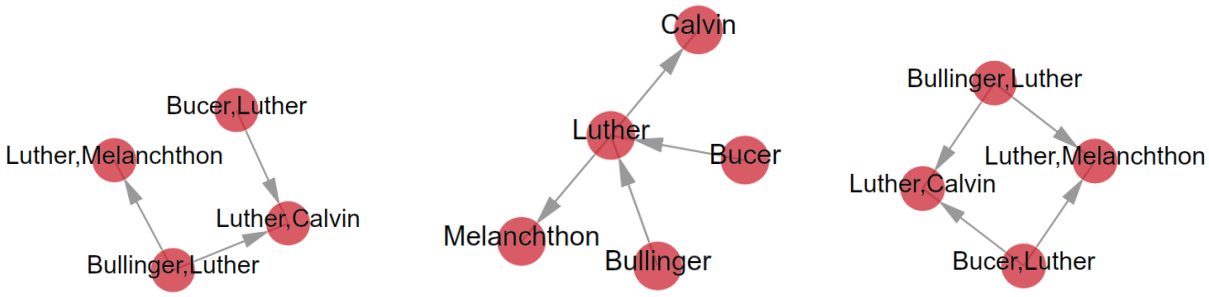
3.3 Analyzing Time-respecting Paths

To address the first research question, of which reformers drove the spread of ideas, I compute the betweenness centrality of nodes in the time-respecting paths. The betweenness centrality of a node measures the extent to which this node passes on information between any two nodes in the network and therefore identifies individuals who facilitate the spread of ideas on a large scale. The betweenness centrality c of a node i is defined as

$$c(i) = \sum_{i \neq j \neq k} p_{ij}(i) \tag{1}$$

where $p_{jk}(i)$ is the number of shortest paths between nodes j and k that pass through node i, and i must neither be the start nor end point of the paths in question: $i \neq j \neq k$.

To address the second research question of which communication patterns were used to spread ideas, I extract the most frequent path length and use this result to inform a qualitative and a quantitative path inspection. The qualitative approach examines driving factors for the occurrence of specific paths, such as relationships of the re-



(a) Observed paths of length one

(b) Observed aggregated network

(c) Randomized paths of length one

Figure 6: Statistical significance tests with first-order network models. 6a Observed higher-order network model where nodes correspond to paths of length one from the data. 6b Observed aggregated network. 6c Randomized higher-order network model where nodes correspond to paths of length one that are extracted from the aggregated network, i.e., paths ignore the temporal ordering of edges. By comparing observed paths of length one (Fig. 6a) with randomized paths of length one (Fig. 6c) sampled from the observed aggregated network (Fig. 6b), the test indicates whether sufficient evidence is provided to claim that observed paths of a specific length are different from random. The example is schematic and not based on real data.

formers involved. The quantitative approach analyzes whether a specific path length is a significant or spurious characteristics of reformers' communication.

The quantitative approach uses higher-order models of paths, which are networks where nodes correspond to a path of a specific length (Scholtes, Wider and Garas 2016). For example, in a second order model a node represents a path of length two, such as Zwingli → Luther → Melanchthon. I use higher-order models in a statistical significance test which compares the extracted time-respecting paths to randomized paths that ignore time (Fig. 6). If time-respecting paths of a specific length are sufficiently different from randomized ones I conclude that the former are representative patterns for the communication network at hand.

One can perform this significance test for several orders simultaneously with multi-order models (Scholtes 2017). They stack higher-order models of different orders in layers, i.e., each layer hosts a network where nodes correspond to paths of a different length. Whereas a higher-order model indicates *that* paths of a specific length (do not) describe the data well, a multi-order model indicates *which* path length describes the data best.

4 Results

4.1 Descriptive Statistics of Temporal Network

Table 1 provides descriptive statistics of the temporal network that I constructed from the letter correspondences. The network is sparse as the large links/nodes ratio shows. Moreover, the short average inter-event time shows that, overall, letters were writ-

Table 1: Descriptive statistics of the temporal letter correspondence network of reformers.

Nodes	3,348
Time-stamped links	30,043
Links/Nodes ratio	8.97
Observation period	1500-01-01 – 1564-06-24[1]
Observation length	64.5 years[2]
Time stamps	10,960[3]
Avg. inter-event time	2.15 days
Min/Max inter-event	1 day/4.12 years[4]

[1] In day-specific time differences: 0–23,550
[2] In number of day-specific time differences: 23,550
[3] Number of unique sending dates of letters.
[3] In day-specific time differences: 1/1,505

ten with a high frequency. However, it does not mean that reformers replied quickly since the temporal network only accounts for the temporal sequence of edges ignoring whether their senders and recipients form time-respecting paths.

4.2 Identifying Influential Reformers for the Spread of Ideas

Figure 7 shows the ten largest betweenness centralities for the aggregated letter correspondence network and the time-respecting paths. Aggregated betweenness values are one magnitude larger than the path-based ones. This is because paths that violate the temporal ordering of edges are also considered for aggregated betweenness leading to overestimated betweenness values.

In both cases, I find the largest betweenness score for Philipp Melanchthon, which holds across different values of δt (see Fig. 2 in Supplementary Material). He seems to be the most influential reformer for the spread of ideas in the network, which answers the first research question. Although these findings match the historiographical reception of Melanchthon as important contributor to the Reformation (Scheible 2016), it is likely caused by a selection bias in our data: 37% of the letters are from Melanchthon's correspondence increasing the chance that these letters form shortest paths that contribute to betweenness.

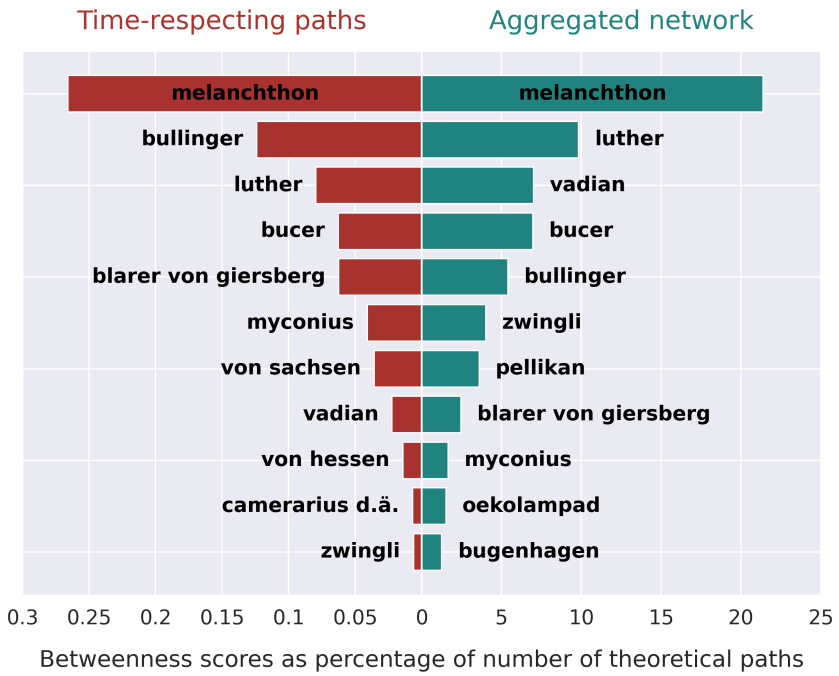


Figure 7: Betweenness centrality scores as percentage of theoretically possible paths. The ten nodes with the largest betweenness scores are shown. Scores for the time-respecting paths are smaller than for the aggregated network since the latter also considers shortest paths where time can run backwards.

4.3 Identifying Communication Patterns in the Spread of Ideas

4.3.1 Quantitative analysis of paths

Figure 8 shows the frequency distribution of path lengths in the temporal network. Paths of length two occur most often, comprising almost 14% of all paths. This result shows that mediated relationships were the most prevalent communication pattern among reformers in our data (Fig 4b), which answers the second research question. Alternative patterns are less common: Diadic communication ($l = 1$, Fig 4a) is dominant in situations where ideas are quickly forgotten ($\delta t <= 7$, see Fig. 3 in Supplementary Material), and chain linking (Fig 4c) is never dominant across all tested values of δt. I perform a statistical significance test with a multi-order network model to examine whether mediating can be attributed to the spread of ideas or is subject to randomness. The model reveals the path length that is most different from random and hence describes the spread of ideas best.

For $15 \leq \delta t \leq 20$, results reveal an optimal model order of two, indicating that paths of length two (mediating) are the characteristic communication pattern in the data (see Fig. 5 in Supplementary Material). In contrast, for $1 \leq \delta t \leq 14$, the optimal order is one, i.e., diadic relationships dominate the spread of ideas. These results partially deviate from the descriptive results above: Although paths of length two occur most frequently in the data for $7 \leq \delta t \leq 14$, the optimal order inferred from the multi-order model is one. I infer that in these cases paths of length two represent a spurious pattern since they would occur equally frequently for randomized paths. This discrepancy un-

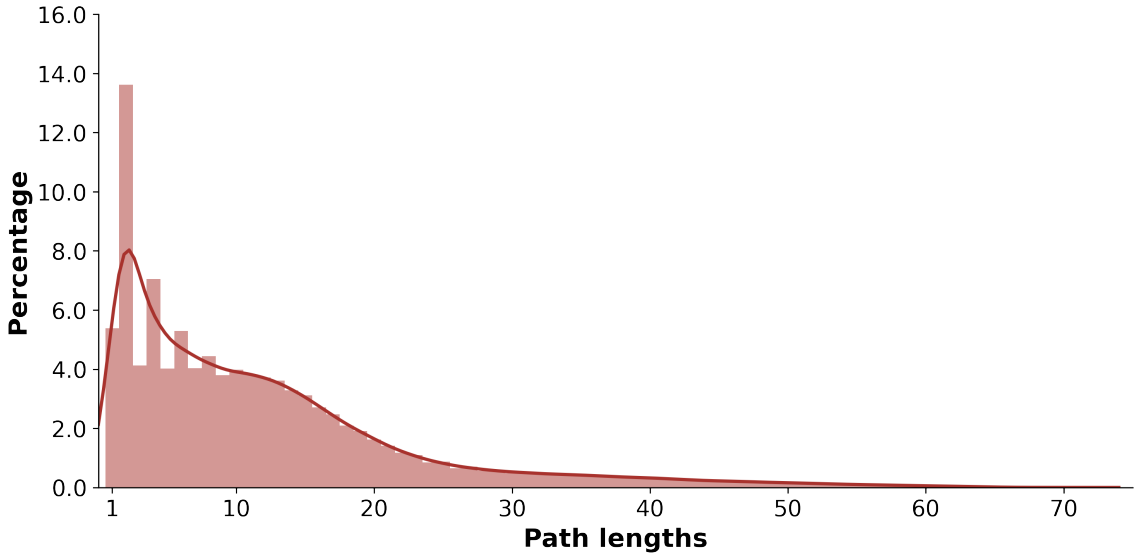


Figure 8: Frequency distribution and density line of path lengths (l) for $\delta t = 15$ days. Paths of length 2 occur most often.

derlines the importance of statistical significance testing over relying on observational patterns alone.

4.3.2 Qualitative analysis of paths

Knowing that paths of length two are meaningful for the spread of ideas, I examine what this meaningfulness entails for the Reformation. I inspect two exemplary paths and analyze how interpersonal relationships between reformers may have given rise to the dominant communication pattern of mediating.

Melanchthon path The first path runs from reformer Andreas Osiander over reformer Philipp Melanchthon to politician Hieronymus Baumgartner. To understand why Melanchthon mediates between Osiander and Baumgartner and why the latter two do not exchange letters directly, we embed the path into a larger historical context: the Osiandrian controversy (see Figure 9). It was one of the largest theological disputes during the Reformation in which its main opponents, Melanchthon and Osiander, argued about the doctrine of justification, i.e., how humans, despite their sins, are declared to be righteous in front of God. Very broadly, Osiander argued that humans cannot lose their righteousness because Christ's righteousness lives in them, whereas Melanchthon thought that humans become righteous through God's forgiveness and hence can lose their righteousness once they lose their faith (Wilson-Kastner 1979; Sparn 2022).

The conflict started when Osiander became professor at the university of Königsberg in 1549 where he fell out with some of his new colleagues over theological questions. Duke Albert of Prussia, a protestant and theology-savvy ruler, had appointed his friend Osiander to professor and supported him throughout the conflict. In a similar fashion, Melanchthon was not fighting alone but had strong supporters from the Lutheran camp, among others his student Baumgartner. Although Baumgartner was not directly involved in the conflict, he was a devout Lutheran, very likely taking clear

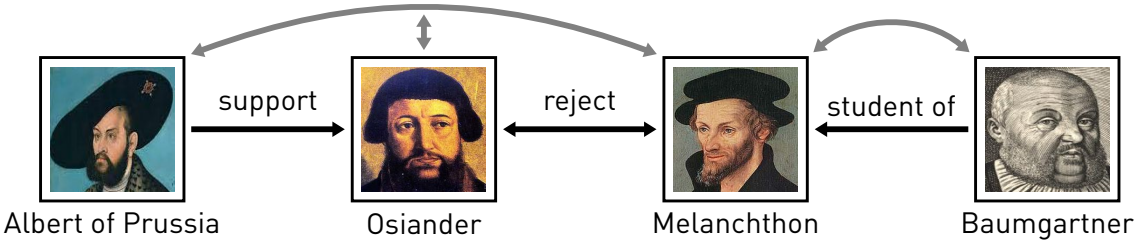


Figure 9: Exemplary time-respecting path of length two: Osiander → Melanchthon → Baumgartner. Letter correspondences (⇢) are embedded in social relations (➞) as part of the Osiandrian controversy.

sides. After having graduated, Baumgartner became a communal politician in Nuremberg where he reformed schools and churches. At the same time, Osiander was a pastor in Nuremberg, increasing the chances that the two knew each other personally.

Why, despite this alleged personal contact, did Osiander and Baumgartner not exchange letters? The simplest answer is that they communicated personally because letters were not needed within the same town. However, this answer leaves open why the communication was not continued once Osiander moved to Königsberg. A second explanation is that the discrepancy between the theological positions of Osiander and Baumgartner was too large for communication. Melanchthon's students could have become more radical in their positions than their teacher and may have been less open to alternative ideas such as the one of Osiander. A third explanation is a lack of interest or knowledge to engage in theological disputes. The Osiandrian controversy revolved around complicated theological questions which were not important for the daily practice of faith. The conflict was an academic debate between scholars, and politicians, such as Baumgartner, may had other priorities than engaging in it.

Zwingli path The second path that I inspect runs from Johannes Oekolampad, via Huldrych Zwingli to Joachim Vadian, all three being Swiss reformers operating in Basel, Zurich, and St. Gallen, respectively. Figure 10 embeds this path into a larger communication context between the protagonists. Whereas Zwingli communicated reciprocally with both Oekolampad and Vadian, Oekolampad sent letters to Vadian but the latter did not reply. This pattern seems typical for Vadian since he did not reply to 66% of people who sent him letters in my data. To explain this unilateral communication and the mediating role of Zwingli, I seek possible explanations in the biographies and personalities of the protagonists.

Oekolampad and Zwingli likely communicated on theological matters. Both had a theological education and represented the Swiss view on Church reform in conflicts with the Lutherans, for example at the Marburg colloquy in 1529. In contrast, Vadian

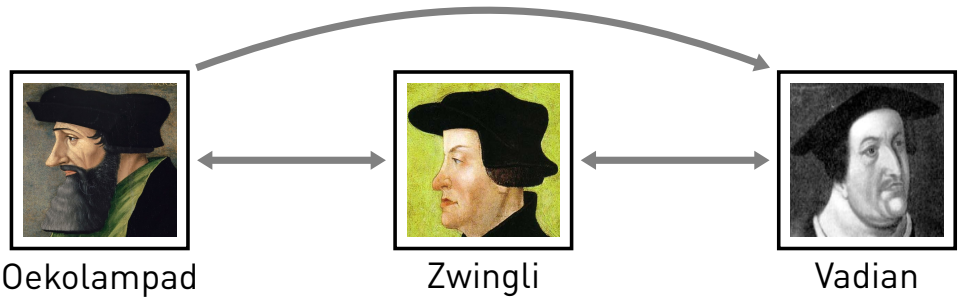


Figure 10: Exemplary time-respecting path of length two: Oekolampad → Zwingli → Vadian with letter correspondences (⇀).

did not have a theological background. He originated from a wealthy and influential merchant family, studied various secular subjects, held influential positions (physician, professor, dean, member of the city council) and eventually became mayor of St. Gallen. He possibly met his friend Zwingli in Vienna, where both had studied arts. Only when Zwingli introduced Protestantism in Zurich, and with that founded an alternative protestant ideology to the Lutheran one, the Zwinglian-Reformed branch, did Vadian become interested in theological questions and used his self-taught knowledge to introduced Protestantism in St. Gallen.

This constellation leads to an unbalanced triad in the letter correspondence network: Zwingli communicates with both of his friends Oekolampad and Vadian, but the latter two do not seem to have a strong relationship. Based on sociological theory, we expect triads to be closed in social networks (Simmel 1908 (2009); Heider 1946; Granovetter 1973). So why does only Oekolampad attempt to close the triad by sending letters to Vadian, but not vice versa?

One possible explanation, is that Vadian was too busy to write to Oekolampad. Besides his extensive studies and career ambitions, Vadian also engaged in extensive study travels and visited friends in other parts of the Holy Roman Empire. However, Vadian's activities did not prevent him to exchange letters with Zwingli, so why did he prioritize Zwingli over Oekolampad as communication partner? Possibly, Oekolampad was not as glamorous as Zwingli. Basel, Oekolampad's place of operation, was a bishopric, i.e., deeply catholic and hence slow to adopt reformist ideas. Oekolampad could not show reformist successes which made him appear backward-oriented in the eyes of his contemporaries. An alternative explanation for the open triad is that Vadian used 'chain letters' to reply to Oekolampad. Chain letters were passed on from recipient to recipient or included passages directed at different people. They were common practice in the 16th century since they reduced paper costs and effort of writing. Whether Vadian included passages for Oekolampad in his letters to Zwingli and whether they relate to the contents of Oekolampad's letters to Vadian has to be investigated when analyzing letter texts.

In summary, I have provided potential explanations of the communication patterns involved in paths around reformers Melanchthon and Zwingli. I deliberately formulated these explanations as possibilities, so that they can be turned into hypotheses and tested in future studies. Of course, the possibility remains that patterns are caused by a selection bias in the data. By engaging with the paths in a qualitative and quantitative manner, this analysis helps to point to potential missing letters.

5 Discussion

This article analyses the transmission of ideas during the protestant Reformation. The aim is to identify the most influential reformer for idea transmission and explain dominant communication patterns like mediating. To address these research questions, I apply a path-based temporal network approach that was hitherto under explored for historical data. Based on a letters correspondence network of reformers, I use the sending dates of letters as edge time stamps to extract time-respecting paths. Time-respecting paths are sequences of nodes connected by chronologically ordered edges with bounded inter-edge times. Temporal ordering is crucial to ensure that information only spreads forward in time. This property is not preserved in aggregated networks where temporal ordering is ignored, allowing information to spread backwards in time and leading to biased topological network measures.

I use betweenness centrality to identify reformers who facilitated the transmission of ideas in the network (RQ 1) and path length frequencies to identify dominant communication patterns (RQ 2). Results reveal that Philipp Melanchthon, the right hand of Martin Luther, was the most influential reformer for the spread of ideas. This finding holds for the time-respecting paths and the aggregated network, but the latter overestimates absolute betweenness values. Moreover, paths of length two dominate indicating that mediating was the main communication pattern. However, this finding depends on specific parameter choices as diadic communication becomes the prevalent pattern of communication when information is quickly forgotten (see Fig. 3 and 5 in Supplementary Material).

Identifying Melanchthon as an influential facilitator for the transmission of ideas seems reasonable because it matches the historigraphical notion of Melanchthon's prominent role during the Reformation (Scheible 2016). As university lecturer, Melanchthon was exposed to many ideas and could pass them on to his students. He also mediated in theological disputes passing on ideas from one faction to another, a practice that resulted in his Confessio Augustana, one of the first rule books on protestant faith.

However, my results may be an artifact of the data since most letters involve Melanchthon as correspondent. This artifact increases the chance that shortest paths run via Melanchthon and hence increase his betweenness centrality. Although the strong representation of Melanchthon in our data is in line with his role as diligent writer, it also points to a strong selection bias: Melanchthon's lifespan overlaps almost entirely with our observation period and previous digitization efforts have focused on prominent figures like him rather than on lesser-known ones.

I used two exemplary paths of length two to explain the dominant communica-

tion pattern of mediating in the light of reformers' biographies. The first path runs from reformer Andreas Osiander over reformer Philipp Melanchthon to politician Hieronymus Baumgartner. Since Osiander and Baumgartner do not exchange letters themselves Melanchthon's role as mediator is strengthened. I proposed three explanations for this constellation: (1) Osiander and Baumgartner had the opportunity to communicate in person because they lived in the same town at the same time, (2) their ideological differences became too large to allow for communication, and (3) Baumgartner prioritized pragmatic concerns over theological details in Osiander's scholarly debates.

The second path runs from Johannes Oekolampad via Huldrych Zwingli to Joachim Vadian, all being Swiss reformers. Similar to the Melanchthon path, Zwingli acts as mediator because Oekolampad sends letters to Vadian but the latter does not reply. Possible explanations for Vadian's absent reciprocity are (1) Oekolampad's alleged lack of progressiveness as resident of a traditionalist bishopric, which made him a less favorable correspondence partner for Vadian than Zwingli, and (2) Vadian's use of chain letters where he sent letters to Zwingli that included passages to Oekolampad.

The results from the Melanchthon- and Zwingli-paths show that network analysis combined with biographical information can help to generate possible explanations for communication patterns but cannot assess their plausibility. To fine tune the interpretation of results, letter texts could be analyzed in addition to the network. Specifically, topics could be extracted from letter texts and be used to construct 'topic paths' between letters based on topic similarity. These topic paths could function as a validation data set for time-respecting paths in networks.

A second avenue of improvement is to increase the representativeness and availability of letter data. A selection bias in digitized letter editions overestimates the importance of famous reformers such as Melanchthon and Luther, whereas the role of lesser known figures is underestimated. Moreover, limited data availability leads to non-representative measures for path parameters when they are computed automatically (see Section 1 in Supplementary Material). Future research should not only digitize ever more letters, but prioritize the digitization of letters from specific individuals so as to make the sample more representative of communication during the Reformation.

Third, future research should address `pathpy`'s simplistic assumption that there is one critical time scale for the whole network in the form of a global δt parameter. Minimal reaction time and memory differ between individuals and may also depend on seasonality, geography, and historical events. Incorporating these heterogeneities will be crucial to capture dynamics of networks more accurately. Some approaches for node-specific time scales already exist (Petrovi, Wegner and Scholtes 2023), but they require tuning for historical data due to data sparseness, which can cause error measures to collapse.

In summary, this analysis used time-respecting paths to incorporate temporal information in historical networks. This approach addresses the problem of achronological information flow present in aggregated networks and temporal network snapshots, and to the best of my knowledge, has not yet been applied to historical data. The time-respecting paths revealed influential reformers for the transmission of ideas and combined with a biographical analysis provided potential explanation for why mediating is the dominant communication patterns among reformers. This study contributes to the important question of accounting for time in historical data analysis.

Disclosure statement

The author reports there are no competing interests to declare.

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Data availability

The data and source code will be made available in a public repository. Until theyr are published there, they can be obtained on request.

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