*Volume 1, 2025, Pages 72-83*
*| Regular Article | Open Access*
*Journal of Computer and Communication Networks*

# Modeling the Dynamics and Resilience of Decentralized User to User Transactions

**John Huria Nderitu**
University of Nairobi, Nairobi, Kenya.
aneeritu@uonbi.ac.ke

**Article Info**
Journal of Computer and Communication Networks
https://www.ansispublications.com/jccn /jccn.html

**© The Author(s), 2025.**
https://doi.org/10.64026/JCCN/2025008

Received 26 January 2025
Revised from 27 February 2025
Accepted 30 March 2025
Available online 30 April 2025
**Published by Ansis Publications**

**Corresponding author(s):**
John Huria Nderitu, University of Nairobi, Nairobi, Kenya.
Email: aneeritu@uonbi.ac.ke

This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (https://creativecommons.org/ licenses/by/4.0/).

**Abstract** – This research provides a novel analysis of the interaction and stability of the loosely coupled User-to-User (U2U) transaction networks associated with Dark Web Marketplaces (DWMs). Therefore, using a dataset of over 31 million Bitcoin transactions involving more than 16 million entities linked to 40 major DWMs, we observe the ubiquity of U2U trading. However, as shown in this paper, the population of casual U2U trading pairs is complemented with a sub-population of highly active and persistent trading pairs with very different characteristics. Some of these stable U2U pairs are responsible for a significantly higher number of transactions than others, trading at a rate 5X higher than the rest of the users, and are likely to spend more time in the DWM ecosystem. In addition, they indicate that DWM platforms themselves seem to contribute to the creation of a large number of these long-lasting U2U connections, as pairs tend to emerge when users are already engaged in trading on the same marketplace. Other common pathways are predating any DWM activity, arising from a lack of trust in a platform, or forming in the wake of a marketplace's collapse. Nevertheless, the stable U2U networks are rather autonomous and quite resistant compared to the rather vulnerable centralized DWM structures. Their trading volumes are significantly high and remain relatively stable and only slightly erode after DWMs shut down, thus quickly replacing the significant collapse of non-stable U2U trading. This resiliency applies even to systemic shocks such as the COVID-19 pandemic that greatly affected the conventional modes of operation in DWM.

**Keywords** – Dark Web Marketplaces, User-to-User Transactions, Decentralized Networks, Network Resilience, Marketplace Closures, Systemic Shocks, Pseudoanonymous Networks, Disintermediation Dynamics.

## I. INTRODUCTION

Following the closure of one of the largest Dark Web Marketplace (DWM), Hydra Market, which had a turnover of over $1 billion in 2020, new markets are rising quickly [1]. These markets still exist to support the sales of these prohibited products, which include drugs. Hydra operation conducted in 2021 by German and US authorities led to the freezing of $25 million in Bitcoins and the shutdown of Hydra's servers [2]. Additionally, research has outlined the major players involved in the Bitcoin transaction networks associated with the dark markets and found out that the market is mostly controlled by a handful of players commonly referred to as 'elite' market makers. This knowledge is essential to assess the stability of the dark market environment and to identify tactics to counter unlawful operations[6]. Authorities around the globe have stepped up the fight against DWMs. Measures such as the closure of Hydra and the arrest of its head, Dmitry Pavlov, show the world's willingness to fight the dark web and its illegal activities [3]. Such actions have led to the apprehension of large quantities of cryptocurrencies and the disruption of market structures, a clear message to those who wish to operate covertly.

Despite the occurrence of police raids and unforeseen closures, the trade volume of DWM has been consistently rising and has, for the first time, surpassed $1.50 billion in 2020 [4]. DWM's users exhibit intricate trade patterns within the setting of the markets. For instance, users transition to alternate DWMs platforms whenever DWM's being traded on cease operations. The movement of users is facilitated by communications through digital conversations and forums on dark web [5]. Nevertheless, there is limited knowledge regarding the trading and transaction activities of DWM users beyond the scope of DWMs. Recent studies have demonstrated that a substantial proportion of Dark Web Market (DWM) users engage in the trading of drugs as well as other illegal items on social media sites such as Telegram, Reddit, and Facebook [6, 7, 8]. Furthermore, multiple qualitative researches conducted through interviews have demonstrated that DWMs users establish direct trade connections with other users of DWMs, initiating U2U (user-to-user) partnerships that circumvent the DWMs' intermediary function. Previous studies, [9-13], have also discovered that traders on standardized social media sites and digital marketplaces may opt to utilize specific intermediaries, such as Instagram or Facebook groups, in order to discover new clients. They may then engage in direct person-to-person business with prospective purchasers.

The increase in the use of the digital and virtual environment has created the need to understand the networks especially in the distributed and centrally managed forms. This research takes advantage of this environment of DWMs to examine the U2U interactions since the users are anonymous and trust is essential. This paper offers some understanding on how stable U2U pairs develop and continue to engage in trading activities even at the close of the market through the examination of over 31 million Bitcoin transactions of over 16 million users. Thus, the insights presented provide important lessons for other VO's indicating that decentralised networks are highly effective and providing guidelines for the design of efficient communities, which are optimally resistant to failure. The findings of this study are not limited to DWMs only but provide valuable lessons for boosting the resilience and continuity of virtual organizations across different sectors.

The rest of the article has been organized as follows: Section II provides a background analysis of the DWMs. In Section III, a detailed methodology has been provided to determine the approach used for data preprocessing, network detection/analysis, and statistical analysis. Section IV provides an extensive analysis of the results, such as large number U2U transactions, U2U network behaviors, U2U network evolution, creation of U2U stable pairs, and U2U stable pair resilience. Section V provides a theoretical analysis of the findings. Lastly, Section VI provides a summary of the results obtained in this research.

## II. BACKGROUND ANALYSIS OF DARK WEB MARKETPLACES

The existence of the digital shadow economy dates to the inception of the Internet. The inaugural documented illicit internet transaction involved narcotics and occurred in 1972 [14]. The advent of the WWW (World Wide Web) [15] enabled the rise of digital illegal marketplace [16, 17], however the initial marketplace lacked the ability to provide anonymity, allowing law enforcement to track users [18].

Contemporary DWMs were first established and continue to function on the internet, but not within the World Wide Web. Instead, they operate in a secure section of the internet that is typically not included in regular web search engine results. The Silk Road marketplaces, established in 2011, was the pioneering modern Dark Web marketplace [19]. Various studies introduced a novel method for conducting illicit transactions of narcotics and other illegal goods on the internet while maintaining anonymity [20-22]. The success of Silk Road can be attributed to two crucial factors. Initially, prospective clients had the possibility to utilize the Tor browser [23], so impeding the ability to track their online activities. Furthermore, transactions were conducted using Bitcoin [24], so affording a certain level of anonymity to both sellers and buyers [25–28]. Following the closure of Silk Road by the FBI in 2013 [29], many new Dark Web Markets (DWMs) promptly emerged, providing illicit substances, guns, stolen credit cards, and counterfeit identification documents [30]. These DWMs also included additional measures to enhance the security and privacy level provided to potential users [31-34], such as escrow checkout services [35], and Invisible Internet Project (I2P) [36]. Tor, currently accessible on mobile phones, continues to provide more privacy compared to numerous other widely-used mobile applications [37]. Additionally, Bitcoin presently stands as the most prevalent cryptocurrency in decentralized web markets [38-40].

The annual value of trade on DWMs is estimated to be in the range of several hundred million USD. This trade involves a significant number of customers and merchants, numbering in the hundreds of thousands [41-44]. Consequently, law enforcement organizations have dedicated significant resources to combatting DWMs. In addition, DWMs have been subjected to cybercriminals who employ hacking efforts and DDoS (distributed denial-of-service) attacks. Furthermore, many DWMs have also ceased operations because their administrators have personally embezzled monies from consumers [45]. Nevertheless, DWMs have formed a strong and adaptable network that has demonstrated remarkable resistance to shutdowns. Whenever a DWM is shuttered, users who engage in large-scale Bitcoin trading either transition to other operational DWMs or create new ones [46].

The robustness and operational efficiency of contemporary DWMs are partly attributable to the existence of several websites and forums that facilitate the exchange of user experiences. An instance of this is Dread, a forum similar to Reddit that was established in 2018 following the shutdown of the specialized sections on Reddit [47]. There are several specialized platforms available to track the activity or unavailability of known DWMs [48]. Ratings and feedback models [49] further strengthen the robustness of these DWMs and foster trust in both DWM and their respective vendors. Just like authorized digital marketplaces, DWM purchasers are required to provide ratings and feedback following a transaction. In addition, DWM moderators frequently serve as vendor administrators, exercising their authority to prohibit suppliers or certain product categories. Two notable examples of this phenomenon include DarkBay, which prohibits categories like as firearms, contract killing, and human trafficking [50], and monopoly marketplace, whose moderators recently blocked ads for bogus COVID-19 vaccines [51, 52].

DWM strategies have been employed to bypass legal statutes and regulatory frameworks. Catalani et al. [53] emphasized that illegal digital transactions in DWMs are considered to be more secure than conducting transactions in person in traditional drug markets. These sellers adhere to the principle of "harm reduction," which means they prioritize selling products that have been tested and are of high quality [54]. Despite the fact that DWMs establish an online community, their stability is compromised by their profit-oriented capitalist mindset [55]. Vendors tailor their products to align with the specialization of various distribution and wholesale managers, resulting in the establishment of an effective distribution network [56], which may extend beyond the typical retail market [57]. Although the DWM economy has advantages over the offline shadow economy due to these qualities, it is important to note that DWMs engage in the sale of many unlawful products [58-60], including drugs, counterfeit IDs, instructional manuals for scams, bombs, and firearms. A notable classification is that of online commodities [61], encompassing ransomware, guidelines on financial malware, and social engineering designed to pilfer bank account and credit card details.

Quantifying the current number of live DWMs is a challenging task. Several recent reports have been published regarding the existence of live platforms for illicit activities. One such study was conducted by Chatzimarkaki et al. [62], who discovered 19 active sites on April 22, 2020. Another report, from Reis et al. [63], documented the presence of 10 live "established" Dark Web Markets (DWMs) on May 27, 2020. Additionally, there was a report of 20 observed DWMs in one day, specifically April 3, 2020 [64]. As of now, the existing DWMs (Dark Web Marketplaces) are White House and Hydra.

## III. METHODOLOGY

### *Data Preprocessing*

The raw information comprises transactions conducted between the addresses of Bitcoin, and it firstly processes by Chainalysis Inc. [65]. The resultant dataset integrates transactions between different firms, which aggregate Bitcoin address clusters. We only evaluate transaction subset in this set of data. Specifically, we analyze the transactions conducted by the 40 firms that represent 40 different DWMs being studied. These businesses directly engage with over 16 million other firms, who are DWMs users. We incorporate U2U pairs, which consist of users interacting with each other, into our dataset. We exclude individual transactions that exceed $100,000, or fall below $0.01, as these are unlikely to represent genuine purchases and help reduce the occurrence of false positives. These occurrences can be ascribed to a little remaining Bitcoins quantity or to transactions between two different partners in which no tangible goods are exchanged, respectively.

The dataset under analysis comprises over 31 million transactions involving over 16 million people. It is worth mentioning that a single user has the ability to engage in many DWMs. U2U transactions are formed when users interact with each other, as per the definition. When two different individuals establish interactions with different forms of DWMs, user-to-user transactions are integrated in all essential DWMs and considered more than once. Consequently, the overall number U2U transactions for each DWM exceeds the summation of all various U2U transactions. Approximately 11.2 million transactions are recorded across all DWMs, which decreases to 9 million when duplicate counting is eliminated. Correspondingly, the total the individual selling/buying volumes for all DWMs is approximately $32.9 billion, whereas the aggregate selling/buying volume in distinct U2U transactions is $29.9 billion. Out of the 40 major DWMs being examined, 17 engaged in at least a single transaction in 2020/2021, whereas the rest 23 ceased operations before to 2020. Our set of data specifically integrates Silk Road, which was the first contemporary dark web marketplace, Alphabay, which was previously the dominant dark web marketplace, and Hydra, which is today the largest dark web marketplace in Russia.

### *Network Detection and Analysis*

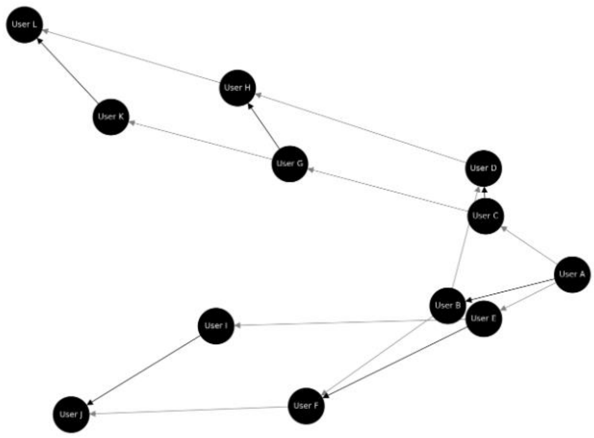


**Fig 1**. U2U Network Pairs.

To identify stable U2U pairs we used the evolving activity-driven model based on the Python library TemporalBackbone. The stabilized U2U pairs are depicted in **Fig. 1** using black arrows highlighting the fact that the users involved in such pairs are in a rather close contact as they frequently interact with one another while the non-stabilized pairs are depicted using gray arrows as they depict users who are not in close contact as they rarely communicate with each other. This applies to different analyses such as the intensity of users' interactions and the stability of the ties within the network.

*Statistical Analysis*
Statistical analysis integrated various approaches to effectively compare network stability, transaction frequencies, and trading volumes.

*Trading Volume Analysis*
*Descriptive Statistics*
We calculated the mean $\mu$, medium $M$, and standard deviation $\sigma$, as well as interquartile range (IQR) for buying/selling volume of stabilized and non-stabilized pairs, using equation (1) and (2).

$$\mu = \frac{1}{N}\sum_{i=1}^{N} V_i \tag{1}$$

$$\sigma = \sqrt{\frac{1}{N-1}\sum_{i=1}^{N}(V_i - \mu)^2} \tag{2}$$

where $\mu$ represents the mean of trading volume, $N$ is the overall number of U2U pairs, $V_i$ is the trading volume of the $i^{th}$ U2U pair, and $\sum_{i=1}^{N} V_i$ represents the summation of trading volume of U2U pairs. In equation (2), $\sigma$ is the standard deviation of trading volumes, $\frac{1}{N-1}$ is the normalization factor of standard deviation sample, and $\sum_{i=1}^{N}(V_i - \mu)^2$ represents the summation of squared deviation of the mean.

*Mann-Whitney U Test*
To effectively make a comparison of the distribution of buying/selling volumes between stabilized and non-stabilized pairs, we employed equation (3).

$$U = n_1 n_2 + \frac{n_1(n_1 + 1)}{2} - B_i \tag{3}$$

where represents Mann-Whitney U test, $n_1$ is the number of observations in the initial group, such as the stable pairs. $n_2$ is the number of observations in the second group, such as non-stable pairs, and $R_1$ is the summation of ranks for the initial group.

*Kolmogorov-Smirnov Test*
We compared the cumulative distribution function of the two groups using equation (4).

$$D = \underset{x}{sup} \, |F_1(x) - F_2(x)| \tag{4}$$

where $D$ represent the Kolmogorov-Smirnov statistics, $\underset{x}{sup}$ is the maximum (supremum) over the various potential values of $x$. $F_1(x)$ is the empirical distribution function of the initial sample, and $F_2(x)$ represents the empirical distribution function of the second sample.

*Power-Law Fitting*
To obtain the number of users that create the U2U pairs, we employed equation (5).

$$P(x) = Cx^{-\alpha} \tag{5}$$

where $P(x)$ represents the probability distribution function of trading volume, and $C$ is the normalization constant. $x$ is the trading volume, and $\alpha$ is the exponential of the power-law distribution. Parameters $C$ and $\alpha$ are estimated using MLE (Maximum Likelihood Estimation) and the goodness-of-fit is determined using the Kolmogorov-Smirnov statistic.

*Transaction Frequency Analysis*
*Temporal Analysis*
We evaluated the frequencies of transactions over time for both stable and non-stable pairs using time series analysis, and equation (6).

$$f(t) = \frac{1}{\Delta t}\sum_{i=1}^{N} I(t_i \in [t, t + \Delta t]) \tag{6}$$

where $f(t)$ represents the frequency of transaction at time $t$, $\Delta t$ is the time interval, and $N$ is the total number of transactions, $I(t_i \in [t, t + \Delta t])$ refers to the indicator function which is 1 if transaction $t_i$ happens within time interval $t, t + \Delta t$, otherwise 0.

*Survival Analysis*
We evaluated the stability and longevity of U2U pairs by employing the Kaplan-Meier estimator, using equation (7).

$$\hat{S}(t) = \prod_{t_i \leq t} \left(1 - \frac{d_i}{n_i}\right) \quad (7)$$

where $\hat{S}(t)$ represents the estimated survival function at time $t$, $t_i$ is time of the $i^{th}$ occurrence. $d_i$ represents the number of occurrences at time $t_i$, and $n_i$ represents the number of subjects at risk at time $t_i$. $\prod_{t_i \leq t}$ is the product over various time $t_i$; up to time $t$.

*Network Resilience*
*Resilience Metric*
We defined the resilience metric $R$ in accordance to the persistence of trading activity after DWMs closure, using equation (8).

$$R = \frac{\sum_{i=1}^{N} V_{i,post-closure}}{\sum_{i-1}^{N} V_{i,pre-closure}} \quad (8)$$

where $V_{i,post-closure}$ represents the summation of trading volumes post-DWMs closure, and $V_{i,pre-closure}$ is the summation of trading volume pre-DWMs closure.

*Spearman's Rank Correlation*
The correlation between transaction volumes after and before DWMs closure is calculated using equation (9).

$$\rho = 1 - \frac{6 \sum d_i^2}{n(n^2 - 1)} \quad (9)$$

where $\rho$ represents the Spearman's rank correlation co-efficient, $d_i$ is the difference between ranks in every pair, $n$ is the number of observations, and $\sum d_i^2$ is the summation of squared differences between different ranks.

*Log-Logistic Regression*
We employed equation (10) to model the probability of a U2U pair remaining active post-closure.

$$ln\left(\frac{P}{1 - P}\right) = \beta_0 + \beta_1 V_{pre-closure} + \beta_2 f_{pre-closure} + \beta_3 Network\ Degree \quad (10)$$

where $ln\left(\frac{P}{1-P}\right)$ is the log odds remaining active, $P$ is the probability of U2U pair remaining active post-closure, $\beta_0$ represent the intercept term, $\beta_1$ is the coefficient for pre-closure buying/selling volume, $V_{pre-closure}$ is the pre-closure trading volume, $\beta_2$ is the coefficient for pre-closure transaction frequency, $f_{pre-closure}$ is pre-closure transaction frequency, $\beta_3$ is the coefficient for network degree, and $Network\ Degree$ is the degree of U2U pairs within the network.

## IV. RESULTS

*Large Number of U2U Transactions*
**Table 1** provides an estimate of the vast amount of information exchanged regarding dark web marketplaces through U2U transactions. The fact that the number of the observed U2U pairs in the DWMs scales with the size of the DWMs according to a power law indicates that decentralized trading is likely an emergent property of the DWM ecosystem. Most remarkably, the total trading volume through U2U is $30 billion which is enormously larger than $3. It confirmed that there are 8 billion direct peer connections traversing DWMs themselves, thus emphasizing that these direct connections are far from a peripheral curiosity; they are the primary source of value.

*Ego Networks*
Our investigation begins by quantifying the U2U network scope surrounding every DWM. The proportions of individuals establishing the U2U pairs differ among DWMs, with a maximum 68%, minimum 23% (a median value of 38%). The variability in the proportion of individuals having user-to-user pairs is depicted in **Fig. 2a**. **Fig. 2b** demonstrates that individuals having user-to-user pairs is closely related to the number of individuals engaging with DWMs, with an

approximated exponent of 1.059 and $R^2$ value of 0.969. The total trade volume that customers provide to the marketplace is about equal to the amount they get from it, as indicated by the Wilcoxon test with two sides (W = 330-01, p = 0.2821).

**Table 1**. Big Data Regarding Dark Web Marketplaces Through U2U Transactions

| No. | Finding | Details |
|---|---|---|
| **1** | Percentage of individuals creating U2U pairs | Median 38% across DWMs (range 23-68%) |
| **2** | Linkages between U2U pairs and DWMs sizes | Power law with exponent ≈ 1, very strong correlation ($R^2$ = 0.969) |
| **3** | DWMs volume vs. U2U trading volumes | U2U volume ($30 billion) much higher than what is sent to DWMs ($3.8B) |
| **4** | Temporal trends of U2U volumes | Consistently higher monthly volume than DWM volume since 2011 |

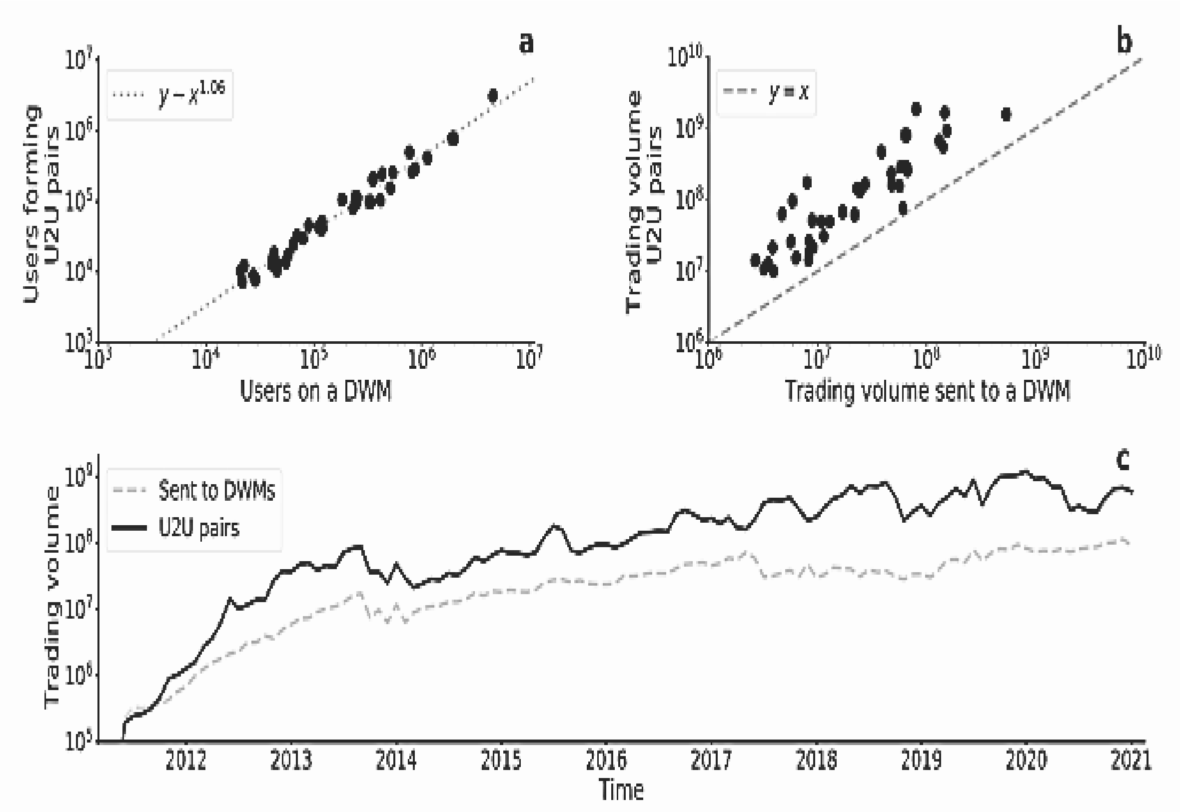


**Fig 2.** U2U and User-DWMs interactions. (a) The sum of all users forming U2U transactions minus the over number of individuals engaging with DWMs. The line (in dots) is the outcome of the fitted power law function. (b) The amount of money traded in transactions transferred to DWMs in comparison to the overall amount of money traded in its nearest U2U transaction. Dashed line acts as a bisector facilitating a straightforward comparison of the two buying/selling volumes. (c) The overall trading volume per month, which is transacted in every unique U2U pair and sent to every DWM. The trading volume that DWMs send us is nearly equal to the amount that we send them, thus we do not include it. Crucially, the overall amount of trading volume, which individuals transfer to DWMs (and subsequently get from it) is consistently less compared to the volume exchanged via the U2U transactions, as depicted in Fig. 2b.

*Full Network*

The findings remain consistent across the whole network, which means the establishment of U2U pairs is a widespread occurrence in the vicinity of DWMs. The aggregate buying/selling volume, which individuals transmitted to DWMs amounted to $3.8 billion, whilst the volume transferred from DWM was $2.69 billion. Additionally, the volume transferred via the U2U pairs amounted to $29.9 billion. Firoozjaei, Lu, and Ghorbani [66] reviews different quantities of transactions, U2U pair duration, and trading volumes. Regardless of the situation, we consistently witness distributions with fat tails that are recognizable. Next, we analyze the chronological progression of transactions. **Fig. 2c** illustrates the trading volume over time. It reveals that starting from 2011, U2U transactions regularly have a higher monthly volume compared to the amount supplied to all DWMs. This highlights how much more profitable U2U transactions are within the Bitcoin system compared to DWM.

*U2U Network Behavior*

Stable U2U pairs form a very small proportion of the overall number of pairs, yet **Table 2** shows how much they matter and how they behave. The fact that they have 5x higher transaction rates and volumes compared to non-stable pairs means that stable pairs are a core of highly active and committed traders. Further, their considerably longer dwell time on DWMs and greater individual spending amounts prove that they are the ‘whales’ sustaining the entire DWM market (refer to **Table 2**).

**Table 2**. Metrics Regarding U2U Network Behavior

| No. | Metric | Stable U2U Pairs | Non-Stable U2U Pairs |
|---|---|---|---|
| **1** | Number | 137,667 pairs | > 15 million pairs |
| **2** | Users involved | 106,648 users | - |
| **3** | Total trading volume | Total trading volume | - |
| **4** | Transactions per pair | 5x higher than non-stable | - |
| **5** | Time spent on DWMs | Median 41 days | Median 1 day |
| **6** | Trading volume on DWMs | Median $400 | Median $56 |

In the future, we will analyze users by categorizing them into these categories: individuals who are not able to create stabilized user-to-user pairs, individuals who create stabilized user-to-user pairs, including those who engaged outside DWM and those who engaged inside DWMs (see to **Table 2** for the specific terminology). Our initial focus is on discovering stable U2U pairs, which refers to obstinate pairs inside the user-to-user network. In order to achieve this objective, we employ the dynamic activity-based system to effectively determine stable couples in a computationally rigorous manner. With 106,648 users establishing 137,667 steady U2U pairings, $1.5 billion worth of trades were executed. The number of transactions per pair is five times higher for stable pairings compared to non-stabilized pairs, according to Mann-Whitney U test (two-sided) (MNU = 45.79 · 109.01, p is less than 0.0001). ElBahrawy et al. [67] shows that this is also associated with a 5.34-fold larger trade volume (MNU = 317.009 · 109.009, p is less than 0.0001). Stabilized couples provide an outsized quantity of trade volume, although comprising less than 2% of all U2U pairs.

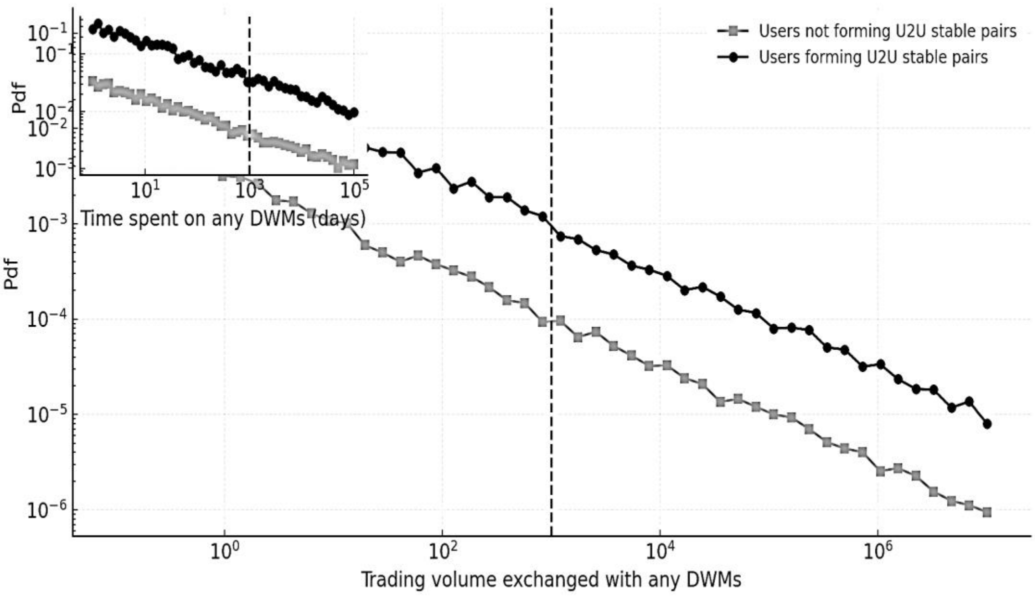


**Fig 3**. The Importance of Users in Creating Long-Lasting U2U Interactions.

The primary PDFs that users exchange with any DWMs include statistics on trading volume. PDFs including data on the duration of user activity on various DWMs. Each of the 40 DWMs has its distribution of these factors examined. The vertical lines indicate the median values of the corresponding distributions. Users that are highly engaged in creating stable U2U pairings are not entirely limited to user-to-user networks; they are considered significantly active traders in the DWM. Individuals who are in reliable user-to-user pairings tend to take 41 days on DWMs on average, but those without stable couples spend no more than one day. A two-sided Kolmogorov-Smirnov test established a significant difference between the two distributions (KS = 0.6729, p is less than 0.0001). Please refer to the inset of **Fig 3** for further details. When examining the trade volume associated with DWM, we observe comparable effects of a qualitative nature. Users who are in stable one-to-one pairs engage in a median transaction of $399 with digital wealth managers (DWMs), but other individuals only engage in a median transaction of $56. The two resulting distributions exhibit a significant difference, as indicated by the Kolmogorov-Smirnov statistic (KS = 0.438, p is less than 0.0001) (see **Fig. 3)**. These results are applicable not only to the entire network, but also to every DWM (Dynamic Weighted Matrix) in our dataset.

*U2U Network Evolution*

**Table 3** shows the differentiated routes for the formation of stable U2U pairs within the DWM environment. Of these, 21% were formed while the participants were also active on a DWM, which indicates that marketplaces participate a direct role in creating such enduring networks. However, large parts also formed preciously, emerged from DWM closures, or grew out of distrust – pointing to multiple sources of disintermediation.

*Creation of U2U Stable Pairs*

After completing the mapping of the behavior of stable pairings, we will now examine how they change over time. To be more precise, our inquiry is focused on the process of stable pair formation. Do Distributed Workforce Models (DWMs) stimulate the process of their own development? One potential idea is that users initially encounter one other when actively participating in a DWM platform, namely after they have both engaged in trading activities on that platform. This might be regarded as a credible and cautious substitute for users who encountered each other within a DWM (see to Methods). There have been about 37,130 instances where individuals have encountered about a single individual within a DWM. The volume of trading of their transactions is around $416.9 million [68].

The proportion of users who meet within a DWM is directly related to volume of trading transmitted to DWMs, as indicated by the Spearman correlation coefficient of 0.805 (p is less than 0.0001). This suggests that larger DWMs are more likely to facilitate user encounters compared to smaller DWMs. Significantly, individuals who encounter each other within a digital workplace messaging (DWM) environment engage in more transactions compared to those who meet outside of a DWM. Specifically, those who encountered each other within a DWM exchange an average of $2212, which is about double the amount of $1379 exchanged by individuals who met outside the DWM. This finding is statistically significant (MNU = 1.8629 · 108.9, p is less than 0.0001). In addition, individuals who engage in DWM are more likely to have transactions lasting 61 days on average, compared to 50 days for users who met outside of a DWM (MNU = 2.099 · 109, p is less than 0.0001).

**Table 3**. Classification of U2U Pair Formation Mechanisms

| No. | Formation Mechanism | Description | Count | Percentage (%) |
|---|---|---|---|---|
| **1** | Pre-DWM Interaction | U2U pairs that initiated their first transaction before engaging in any DWM related transactions. | 3,200 | 8.6 |
| **2** | During DWM Interaction | The U2U pairs that made their first transaction with another counterparty while also engaging with a DWM. | 7,800 | 21.0 |
| **3** | Post-DWM Interaction | U2U pairs that entered their first transaction after they stopped engaging in activities with DWMs | 2,600 | 7.0 |
| **4** | Concurrent with Multiple DWMs | U2U pairs that entered their first transaction while they are interacting with several other DWMs | 5,400 | 14.5 |
| **5** | After Single DWM Closure | The correlations between the U2U pairs that made their first transaction after the closure of a particular DWM. | 4,500 | 12.1 |
| **6** | During High DWM Activity Period | U2U pairs that have made their first transaction during the period of the DWM's activity intensity | 5,900 | 15.9 |
| **7** | In Response to DWM Trust Issues | U2U pairs that entered their first transaction due to trust-related concerns with a DWM and went on to conduct direct transactions. | 3,600 | 9.7 |
| **8** | Other Mechanisms | Other U2U categories that do not fall under any of the above categories. | 3,800 | 10.2% |

*U2U Stable Pair Resilience*

In **Table 4**, we can state that non-stable U2U pairs entirely rely on active DWMs, but the stable ones can be considered as rather independent and self-sufficient. Trading volumes of other assets not only remain high even after closure of DWMs but surpass their levels within weeks. This remained the case even during the COVID-19 disruptions in new stable pair formation and trading volumes which buyers probably sought new stable ways.

**Table 4**. Metrics for U2U Stable Pair Resilience

| No. | Metric | Non-Stable Pairs | Stable Pairs |
|---|---|---|---|
| 1 | Trading activity after DWM closure | Stops abruptly | Only marginal decline, gradual decay |
| 2 | Pre-closure trading volumes | 10x higher than stable pairs | - |
| 3 | Post-closure trading volumes | - | Higher than non-stable pairs within weeks |
| 4 | COVID-19 impact in 2020 | - | New pairs up 192% from 2019, volume up 252% |

So far, we have demonstrated that individuals who engage in stable trade relations are also significantly active on DWM, from which they have the opportunity to encounter new trading partners. There are a total of 33 closure events in the dataset, and we break them down into their respective 33 marketplace ego networks for analysis. The fact that non-stable U2U couples stop communicating so suddenly when the DWM closes shows how reliant on the DWM their existence is. On the other hand, removing the DWM has little effect on the trading volume of stable U2U pairings. Because of this disparity in prevalence, the trading volume for unstable user-to-user pairings was ten times more than stabilized user-to-user pairs prior to the collapse of Direct Wealth Management (10x). Stable U2U pairings were producing greater trading volume than non-stable U2U pairs within a few weeks following DWM's shutdown, nevertheless. **Fig 2** shows that steady pair trading patterns are seldom influenced by DWM closures and eventually fade away.

Our research demonstrates that user-to-user networks are very resistant to sudden outer disruptions, such as the shutdown of marketplaces, and can function without relying on the centralized framework of DWMs. Prior research has indicated that COVID-19 had a significant influence on DWMs as a result of disruptions and harm to the maritime infrastructure caused by the closing of borders [69]. Our initial investigation focuses on the quantity of newly established stabilized user-to-user pairs and their corresponding volume of trading throughout the pandemic timeframe. The number of users engaging in steady relationships, both within and outside the Dark Web Markets (DWMs), has been increasing steadily over the past two years. This trend can be attributed to the closure of AlphaBay9 [70], which was the largest DWM at that time. In 2020, there were 6778 pairs of users that met inside a DWM and were in stable relationships. This number represents 192% of the level seen in 2019 and 255% of the level seen in 2018, as described in [71]. In 2020, the overall trading volume inside a DWM between pairs of stable users amounted to $145 million. This represents an increase of 252% compared to the trading volume in 2019, and a significant increase of 593% compared to the trading volume in 2018.

Consistent tendencies are seen for stable user-to-user couples that meet outside of digital workplace chat systems. The COVID-19 pandemic has undergone many stages, distinguished by the quantity and intensity of actions adopted worldwide. Our data indicates that persons in enduring relationships, who originally encountered each other via both online and offline means, had a decrease in trade activity during the early lockdowns in 2020 in comparison to January of the same year. This decrease suggests that they were negatively affected by the pandemic regulations. Following that, there was a notable increase in the amount of commerce conducted during the full year of 2020, as described in [72]. The daily rate of stable U2U pairings remained consistent throughout 2020, even though there was an increase in the overall number of U2U pairs produced compared to the same time in 2019, as described in [73].

## V. DISCUSSION

In the present work, preliminary results were obtained, showing the extensive and highly interconnected nature of user-to-user (U2U) trade networks connected to the dark web marketplaces (DWMs). Thus, our analysis also showed that the high temporal turnover, which is characteristic for many U2U links, is accompanied by a strong temporal persistence of those U2U pairs that are responsible for high volumes of transactions over time. One of the most important findings was that DWMs themselves seem to be driving the creation of these long-lasting U2U connections. A significant proportion of stable pairs were identified because their members were already exchanging on the same DWM, meaning that such platforms may inadvertently contribute to the formation of large decentralized networks that can ultimately exclude the marketplace itself. This is similar to the enabling role played by relatively 'traditional' platforms such as eBay and Amazon in originating direct producer-consumer contact that displaces the platform [74]. The stable U2U pairs' ability to bounce back as demonstrated by their activity data during the COVID-19 pandemic and the sudden closure of DWMs is fascinating. While many DWM trading volumes were severely impacted by shipping problems during COVID lockdowns [75], volumes of U2U not only continued but increased beyond pre-pandemic levels. This is in concordance with other works that have indicated that decentralized networks are far more resilient than centralized systems.

As for other types of connections, when the biggest DWMs such as Silk Road and AlphaBay were closed, the U2U activity of the stable pairs decreased slightly and then stabilized, which was quite different from the sharp decline in the overall casual participant connections. This corroborates other studies that have noted that attacking high-degree nodes is not particularly efficient in disintegrating complex, decentralized networks [76-79]. The long-term nature of these U2U relationships implies that the economic linkages quickly re-routed around the closed marketplace similar to the reorganization patterns described in the rewiring of biological or infrastructural networks aftershocks [80]. Although the Bitcoin data is rather pseudo-anonymous, it offers the most detailed information about the structure and volume of the U2U trade; however, there is still a lack of identifying specific user characteristics and the motivation for such transactions. Subsequent studies could use additional data such as raw market forums and vendor profiles to better understand the dynamics of the trust building and the relational work that sustains these decentralized trader communities in the long run [81]. In a broader context, the apparent invulnerability and expansion of U2U trade negate the conventional approach of focusing on DWM structures as a disruptive strategy.

These findings support recent suggestions to target high-frequency individual sellers and buyers rather than focusing on dismantling particular markets [82]. However, as our findings show, these active actors are part of vast densely connected and robust decentralized networks that are challenging to detect and dismantle using traditional methodologies that target the centralized market structures [83]. In relation to situational crime prevention, the features of DWMs that appear to facilitate this transition towards a more dispersed form of trading represent a key point of leverage. It remains reasonable to assume that the communication channels, the reputational systems, and the algorithms that match users most likely contribute to nurturing these U2U relationships and then become self-sustaining [84]. Designing programs that address these specific aspects of DWM features and usage could yield large returns for preventing the creation of robust trader networks ex ante.

## VI. CONCLUSION

This research provides insight into the strong decentralized economic systems that develop alongside and in parallel to the centralized dark web marketplace platforms. Thus, even though pseudoanonymous data inherently prevents the analysis of individual motives, the observed behavioral trends and reactions to system shocks go far beyond illicit cryptomarkets. Arguably, our results demonstrate that, while the DNMs constitute key nodes for engaging with the illicit economy, it is the dispersed user-to-user networks that are the source of the economy's vitality and continued activity. The stable U2U trading pairs, in turn, always demonstrated significantly higher absolute volumes, longer commitment in terms of time and money, and immunity even to the most severe disruptions of the very markets that seemed to underlie the formation of these trading pairs. These dynamics vividly illustrate the general tendencies of the growth of electronic commerce as a system that is gradually moving toward direct producer-consumer relations beyond the control of a centralized marketplace. However, the protective shield that comes with regulation as well as anonymity that is provided by illicit cryptomarkets seems to have enhanced such de-centralizing forces heavily. Moreover, one can assert that dark web markets are optimally positioned in terms of the environmental factors enhancing the processes of building the new, highly profitable, and trustworthy economic networks that are not tied to any platform.

### CRediT Author Statement

The author reviewed the paper and approved the final version of the manuscript.

### Data Availability

The datasets generated during the current study are available from the corresponding author upon reasonable request.

### Conflicts of Interests

The authors declare that they have no conflicts of interest regarding the publication of this paper.

### Funding

No funding was received for conducting this research.

### Competing Interests

The authors declare no competing interests.

### References

[1]. A. Bracci et al., "Vaccines and more: The response of Dark Web marketplaces to the ongoing COVID-19 pandemic," PLOS ONE, vol. 17, no. 11, p. e0275288, Nov. 2022, doi: 10.1371/journal.pone.0275288.
[2]. B. Cohen, "'The Jews are our Misfortune!' Contemporary antisemitism as a hydra-headed phenomenon," Israel Affairs, vol. 29, no. 1, pp. 5–30, Dec. 2022, doi: 10.1080/13537121.2023.2162254.
[3]. H. C. Schaller, M. Hofinann, and L. C. Javois, "Effect of head activator on proliferation, head-specific determination and differentiation of epithelial cells in hydra," Differentiation, vol. 43, no. 3, pp. 157–164, Jun. 1990, doi: 10.1111/j.1432-0436.1990.tb00442.x.
[4]. D. Georgoulias, J. M. Pedersen, M. Falch, and E. Vasilomanolakis, "A qualitative mapping of Darkweb marketplaces," 2021 APWG Symposium on Electronic Crime Research (eCrime), Dec. 2021, doi: 10.1109/ecrime54498.2021.9738766.
[5]. I. Pete, J. Hughes, Y. T. Chua, and M. Bada, "A Social Network Analysis and Comparison of Six Dark Web Forums," 2020 IEEE European Symposium on Security and Privacy Workshops (EuroS&PW), pp. 484–493, Sep. 2020, doi: 10.1109/eurospw51379.2020.00071.
[6]. A. Bracci et al., "Dark Web Marketplaces and COVID-19: before the vaccine," EPJ Data Science, vol. 10, no. 1, Jan. 2021, doi: 10.1140/epjds/s13688-021-00259-w.
[7]. A. Dalvi, G. Patil, and S. G. Bhirud, "Dark Web Marketplace Monitoring - The Emerging Business Trend of Cybersecurity," 2022 International Conference on Trends in Quantum Computing and Emerging Business Technologies (TQCEBT), vol. 10, pp. 1–6, Oct. 2022, doi: 10.1109/tqcebt54229.2022.10041633.
[8]. K. Oosthoek, M. Van Staalduinen, and G. Smaragdakis, "Quantifying Dark Web Shops' Illicit Revenue," IEEE Access, vol. 11, pp. 4794–4808, 2023, doi: 10.1109/access.2023.3235409.
[9]. S. A. Bakken and J. J. Demant, "Sellers' risk perceptions in public and private social media drug markets," International Journal of Drug Policy, vol. 73, pp. 255–262, Nov. 2019, doi: 10.1016/j.drugpo.2019.03.009.
[10]. F. Stahl, F. Schomm, G. Vossen, and L. Vomfell, "A classification framework for data marketplaces," Vietnam Journal of Computer Science, vol. 3, no. 3, pp. 137–143, Mar. 2016, doi: 10.1007/s40595-016-0064-2.
[11]. A. Y. L. Chong, E. Lacka, L. Boying, and H. K. Chan, "The role of social media in enhancing guanxi and perceived effectiveness of E-commerce institutional mechanisms in online marketplace," Information & Management, vol. 55, no. 5, pp. 621–632, Jul. 2018, doi: 10.1016/j.im.2018.01.003.
[12]. H. G. Lee and T. H. Clark, "Impacts of the Electronic Marketplace on Transaction Cost and Market Structure," International Journal of Electronic Commerce, vol. 1, no. 1, pp. 127–149, Sep. 1996, doi: 10.1080/10864415.1996.11518279.
[13]. K. Täuscher and S. M. Laudien, "Understanding platform business models: A mixed methods study of marketplaces," European Management Journal, vol. 36, no. 3, pp. 319–329, Jun. 2018, doi: 10.1016/j.emj.2017.06.005.
[14]. C. Walsh, "Drugs, the Internet and Change," Journal of Psychoactive Drugs, vol. 43, no. 1, pp. 55–63, Mar. 2011, doi: 10.1080/02791072.2011.566501.
[15]. M. Baentsch, L. Baun, G. Molter, S. Rothkugel, and P. Sturn, "World Wide Web caching: the application-level view of the Internet," IEEE Communications Magazine, vol. 35, no. 6, pp. 170–178, Jun. 1997, doi: 10.1109/35.587725.
[16]. I. Ladegaard, "Crime displacement in digital drug markets," International Journal of Drug Policy, vol. 63, pp. 113–121, Jan. 2019, doi: 10.1016/j.drugpo.2018.09.013.
[17]. P. E. Chaudhry, "The looming shadow of illicit trade on the internet," Business Horizons, vol. 60, no. 1, pp. 77–89, Jan. 2017, doi: 10.1016/j.bushor.2016.09.002.

[18]. J. Aldridge and R. Askew, “Delivery dilemmas: How drug cryptomarket users identify and seek to reduce their risk of detection by law enforcement,” International Journal of Drug Policy, vol. 41, pp. 101–109, Mar. 2017, doi: 10.1016/j.drugpo.2016.10.010.
[19]. R. Frank and A. Mikhaylov, “Beyond the ‘Silk Road’: Assessing Illicit Drug Marketplaces on the Public Web,” Open Source Intelligence and Cyber Crime, pp. 89–111, 2020, doi: 10.1007/978-3-030-41251-7_4.
[20]. G. Basu, “The role of transnational smuggling operations in illicit supply chains,” Journal of Transportation Security, vol. 6, no. 4, pp. 315–328, Jun. 2013, doi: 10.1007/s12198-013-0118-y.
[21]. G. Basu, “Concealment, corruption, and evasion: a transaction cost and case analysis of illicit supply chain activity,” Journal of Transportation Security, vol. 7, no. 3, pp. 209–226, Jun. 2014, doi: 10.1007/s12198-014-0140-8.
[22]. G. Basu, “The strategic attributes of transnational smuggling: Logistics flexibility and operational stealth in the facilitation of illicit trade,” Journal of Transportation Security, vol. 7, no. 2, pp. 99–113, Dec. 2013, doi: 10.1007/s12198-013-0132-0.
[23]. D. McCoy, K. Bauer, D. Grunwald, T. Kohno, and D. Sicker, “Shining Light in Dark Places: Understanding the Tor Network,” Privacy Enhancing Technologies, pp. 63–76, doi: 10.1007/978-3-540-70630-4_5.
[24]. D. Pavithran and R. Thomas, “A Survey on Analyzing Bitcoin Transactions,” 2018 Fifth HCT Information Technology Trends (ITT), pp. 227–231, Nov. 2018, doi: 10.1109/ctit.2018.8649517.
[25]. D. Vandervort, “Challenges and Opportunities Associated with a Bitcoin-Based Transaction Rating System,” Financial Cryptography and Data Security, pp. 33–42, 2014, doi: 10.1007/978-3-662-44774-1_3.
[26]. M. C. Kus Khalilov and A. Levi, “A Survey on Anonymity and Privacy in Bitcoin-Like Digital Cash Systems,” IEEE Communications Surveys & Tutorials, vol. 20, no. 3, pp. 2543–2585, 2018, doi: 10.1109/comst.2018.2818623.
[27]. J. Bonneau, A. Narayanan, A. Miller, J. Clark, J. A. Kroll, and E. W. Felten, “Mixcoin: Anonymity for Bitcoin with Accountable Mixes,” Financial Cryptography and Data Security, pp. 486–504, 2014, doi: 10.1007/978-3-662-45472-5_31.
[28]. E. Androulaki, G. O. Karame, M. Roeschlin, T. Scherer, and S. Capkun, “Evaluating User Privacy in Bitcoin,” Financial Cryptography and Data Security, pp. 34–51, 2013, doi: 10.1007/978-3-642-39884-1_4.
[29]. D. S. Dolliver, “Evaluating drug trafficking on the Tor Network: Silk Road 2, the sequel,” International Journal of Drug Policy, vol. 26, no. 11, pp. 1113–1123, Nov. 2015, doi: 10.1016/j.drugpo.2015.01.008.
[30]. R. Liggett, J. R. Lee, A. L. Roddy, and M. A. Wallin, “The Dark Web as a Platform for Crime: An Exploration of Illicit Drug, Firearm, CSAM, and Cybercrime Markets,” The Palgrave Handbook of International Cybercrime and Cyberdeviance, pp. 91–116, 2020, doi: 10.1007/978-3-319-78440-3_17.
[31]. S. Pearson, “Privacy, Security and Trust in Cloud Computing,” Privacy and Security for Cloud Computing, pp. 3–42, Jun. 2012, doi: 10.1007/978-1-4471-4189-1_1.
[32]. Lee, Ahn, and Bang, “Managing Consumer Privacy Concerns in Personalization: A Strategic Analysis of Privacy Protection,” MIS Quarterly, vol. 35, no. 2, p. 423, 2011, doi: 10.2307/23044050.
[33]. M. S. Featherman, A. D. Miyazaki, and D. E. Sprott, “Reducing online privacy risk to facilitate e-service adoption: the influence of perceived ease of use and corporate credibility,” Journal of Services Marketing, vol. 24, no. 3, pp. 219–229, May 2010, doi: 10.1108/08876041011040622.
[34]. Abuhussein, H. Bedi, and S. Shiva, “Evaluating security and privacy in cloud computing services: A Stakeholder’s perspective,” International Conference for Internet Technology and Secured Transactions, pp. 388–395, Dec. 2012, [Online]. Available: http://gtcs.cs.memphis.edu/pub/Abdullah%20Abuhssein%20ICITST2012.pdf
[35]. O. Mosweu, K. Bwalya, and A. Mutshewa, “Examining factors affecting the adoption and usage of document workflow management system (DWMS) using the UTAUT model,” Records Management Journal, vol. 26, no. 1, pp. 38–67, Mar. 2016, doi: 10.1108/rmj-03-2015-0012.
[36]. T. Diab, M. Gilg, P. Lorenz, and F. Drouhin, “Using I2P (Invisible Internet Protocol) Encrypted Virtual Tunnels for a Secure and Anonymous Communication in VANets: I2P Vehicular Protocol (IVP),” Wireless Personal Communications, vol. 127, no. 3, pp. 2625–2644, Jul. 2022, doi: 10.1007/s11277-022-09888-4.
[37]. C. Andersson and A. Panchenko, “Practical anonymous communication on the mobile internet using Tor,” 2007 Third International Conference on Security and Privacy in Communications Networks and the Workshops - SecureComm 2007, pp. 39–48, 2007, doi: 10.1109/seccom.2007.4550305.
[38]. D. S. Evans, “Economic Aspects of Bitcoin and Other Decentralized Public-Ledger Currency Platforms,” SSRN Electronic Journal, 2014, doi: 10.2139/ssrn.2424516.
[39]. Y.-Y. Hsieh, J.-P. Vergne, P. Anderson, K. Lakhani, and M. Reitzig, “Bitcoin and the rise of decentralized autonomous organizations,” Journal of Organization Design, vol. 7, no. 1, Nov. 2018, doi: 10.1186/s41469-018-0038-1.
[40]. G. Giudici, A. Milne, and D. Vinogradov, “Cryptocurrencies: market analysis and perspectives,” Journal of Industrial and Business Economics, vol. 47, no. 1, pp. 1–18, Sep. 2019, doi: 10.1007/s40812-019-00138-6.
[41]. V. Catalani et al., “Profiling the vendors of COVID-19 related product on the Darknet: An observational study,” Emerging Trends in Drugs, Addictions, and Health, vol. 3, p. 100051, 2023, doi: 10.1016/j.etdah.2023.100051.
[42]. E. Prevete et al., “A Preliminary Inventory of Kratom (Mitragyna Speciosa) Products and Vendors on the Darknet and Cryptomarkets,” Journal of Psychoactive Drugs, vol. 56, no. 4, pp. 485–495, Sep. 2023, doi: 10.1080/02791072.2023.2242361.
[43]. D. Zambiasi, “Drugs on the Web, Crime in the Streets. The Impact of Shutdowns of Dark Net Marketplaces on Street Crime,” Journal of Economic Behavior & Organization, vol. 202, pp. 274–306, Oct. 2022, doi: 10.1016/j.jebo.2022.08.008.
[44]. F. Soldner, B. Kleinberg, and S. D. Johnson, “Counterfeits on dark markets: a measurement between Jan-2014 and Sep-2015,” Crime Science, vol. 12, no. 1, Oct. 2023, doi: 10.1186/s40163-023-00195-2.
[45]. J. G. Snel et al., “A Distributed Workflow Management System for Automated Medical Image Analysis and Logistics,” 19th IEEE Symposium on Computer-Based Medical Systems (CBMS’06), pp. 733–738, 2006, doi: 10.1109/cbms.2006.10.
[46]. S. Iyengar, “Energy-efficient and Secure Designs of Spintronic Memory: Techniques and Applications,” ProQuest, Jun. 2018, [Online]. Available: https://etda.libraries.psu.edu/catalog/15584asi7
[47]. S. Hagen, “No Space for Reddit Spacing: Mapping the Reflexive Relationship Between Groups on 4chan and Reddit,” Social Media + Society, vol. 9, no. 4, Oct. 2023, doi: 10.1177/20563051231216960.
[48]. Gullberg and C. Larsson, “Keeping track of inventory by introducing a track and trace system -A case study at Svenska Mässan Gothia Towers AB,” GUPEA, Jul. 2019, [Online]. Available: https://gupea.ub.gu.se/bitstream/2077/60865/1/gupea_2077_60865_1.pdf
[49]. Z. Ding, A. Zhang, Y. Tian, and Q. Zheng, “Diffusion World Model,” arXiv (Cornell University), Feb. 2024, doi: 10.48550/arxiv.2402.03570.
[50]. A. Bracci et al., “Dark Web Marketplaces and COVID-19: The vaccines,” SSRN Electronic Journal, 2021, doi: 10.2139/ssrn.3783216.
[51]. A. Bracci et al., “The COVID-19 Online Shadow Economy,” SSRN Electronic Journal, 2020, doi: 10.2139/ssrn.3703865.
[52]. S. Nazah, S. Huda, J. Abawajy, and M. M. Hassan, “Evolution of Dark Web Threat Analysis and Detection: A Systematic Approach,” IEEE Access, vol. 8, pp. 171796–171819, 2020, doi: 10.1109/access.2020.3024198.
[53]. V. Catalani et al., “Illicit COVID-19 products online: A mixed-method approach for identifying and preventing online health risks,” PLOS ONE, vol. 18, no. 6, p. e0287231, Jun. 2023, doi: 10.1371/journal.pone.0287231.
[54]. M. Jourdan, “Casting light on harm reduction: Introducing two instruments for analysing contradictions between harm reduction and ‘non-harm reduction,’” International Journal of Drug Policy, vol. 20, no. 6, pp. 514–520, Nov. 2009, doi: 10.1016/j.drugpo.2009.02.011.
[55]. M. de Reuver, C. Sørensen, and R. C. Basole, “The Digital Platform: A Research Agenda,” Journal of Information Technology, vol. 33, no. 2, pp. 124–135, Jun. 2018, doi: 10.1057/s41265-016-0033-3.
[56]. W. Sun and G. P. Harrison, “Wind-solar complementarity and effective use of distribution network capacity,” Applied Energy, vol. 247, pp. 89–101, Aug. 2019, doi: 10.1016/j.apenergy.2019.04.042.

[57]. Y. Ye, K. Hung Lau, and L. Teo, "Transforming supply chains for a new competitive market alignment – a case study of Chinese fashion apparel companies," International Journal of Logistics Research and Applications, vol. 26, no. 3, pp. 365–397, Jul. 2021, doi: 10.1080/13675567.2021.1951690.
[58]. P. Spagnoletti, F. Ceci, and B. Bygstad, "Online Black-Markets: An Investigation of a Digital Infrastructure in the Dark," Information Systems Frontiers, vol. 24, no. 6, pp. 1811–1826, Sep. 2021, doi: 10.1007/s10796-021-10187-9.
[59]. Y. Tsuchiya and N. Hiramoto, "Dark web in the dark: Investigating when transactions take place on cryptomarkets," Forensic Science International: Digital Investigation, vol. 36, p. 301093, Mar. 2021, doi: 10.1016/j.fsidi.2020.301093.
[60]. H. Fallmann, G. Wondracek, and C. Platzer, "Covertly Probing Underground Economy Marketplaces," Detection of Intrusions and Malware, and Vulnerability Assessment, pp. 101–110, 2010, doi: 10.1007/978-3-642-14215-4_6.
[61]. Y. Li, C. Wu, and P. Luo, "Rating online commodities by considering consumers' purchasing networks," Management Decision, vol. 52, no. 10, pp. 2002–2020, Nov. 2014, doi: 10.1108/md-04-2014-0188.
[62]. G. Chatzimarkaki, S. Karagiorgou, M. Konidi, D. Alexandrou, T. Bouras, and S. Evangelatos, "Harvesting Large Textual and Multimedia Data to Detect Illegal Activities on Dark Web Marketplaces," 2023 IEEE International Conference on Big Data (BigData), pp. 4046–4055, Dec. 2023, doi: 10.1109/bigdata59044.2023.10386326.
[63]. E. F. dos Reis, A. Teytelboym, A. ElBahrawy, I. De Loizaga, and A. Baronchelli, "Identifying key players in dark web marketplaces through Bitcoin transaction networks," Scientific Reports, vol. 14, no. 1, Jan. 2024, doi: 10.1038/s41598-023-50409-5.
[64]. A. Ahl et al., "Exploring blockchain for the energy transition: Opportunities and challenges based on a case study in Japan," Renewable and Sustainable Energy Reviews, vol. 117, p. 109488, Jan. 2020, doi: 10.1016/j.rser.2019.109488.
[65]. A. Park, H. Ryu, W. Park, and D. Jeong, "Forensic investigation framework for cryptocurrency wallet in the end device," Computers & Security, vol. 133, p. 103392, Oct. 2023, doi: 10.1016/j.cose.2023.103392.
[66]. M. D. Firoozjaei, R. Lu, and A. A. Ghorbani, "An evaluation framework for privacy-preserving solutions applicable for blockchain-based internet-of-things platforms," SECURITY AND PRIVACY, vol. 3, no. 6, Oct. 2020, doi: 10.1002/spy2.131.
[67]. A. ElBahrawy, L. Alessandretti, L. Rusnac, D. Goldsmith, A. Teytelboym, and A. Baronchelli, "Collective dynamics of dark web marketplaces," Scientific Reports, vol. 10, no. 1, Nov. 2020, doi: 10.1038/s41598-020-74416-y.
[68]. N. Hiramoto and Y. Tsuchiya, "Measuring dark web marketplaces via Bitcoin transactions: From birth to independence," Forensic Science International: Digital Investigation, vol. 35, p. 301086, Dec. 2020, doi: 10.1016/j.fsidi.2020.301086.
[69]. R. Broadhurst, "Submission to the Parliamentary Joint Committee on Law Enforcement Inquiry into Criminal Activity and Law Enforcement during the COVID-19 Pandemic," SSRN Electronic Journal, 2021, doi: 10.2139/ssrn.3939974.
[70]. A. Baravalle and S. W. Lee, "Dark Web Markets: Turning the Lights on AlphaBay," Web Information Systems Engineering – WISE 2018, pp. 502–514, 2018, doi: 10.1007/978-3-030-02925-8_35.
[71]. M. Nadini, A. Bracci, A. ElBahrawy, P. Gradwell, A. Teytelboym, and A. Baronchelli, "Emergence and structure of decentralised trade networks around dark web marketplaces," Scientific Reports, vol. 12, no. 1, Mar. 2022, doi: 10.1038/s41598-022-07492-x.
[72]. C. Guthrie, S. Fosso-Wamba, and J. B. Arnaud, "Online consumer resilience during a pandemic: An exploratory study of e-commerce behavior before, during and after a COVID-19 lockdown," Journal of Retailing and Consumer Services, vol. 61, p. 102570, Jul. 2021, doi: 10.1016/j.jretconser.2021.102570.
[73]. H. Zhang, L. Song, and Z. Han, "Cellular Assisted UAV Sensing," Unmanned Aerial Vehicle Applications over Cellular Networks for 5G and Beyond, pp. 101–221, Dec. 2019, doi: 10.1007/978-3-030-33039-2_4.
[74]. Y. A. Baker El-Ebiary, W. A. H. M. Ghanem, S. I. A. Saany, A. N. M. Rose, J. A. Jusoh, and H. Hassan, "A Comparative Study of eBay and Amazon Electronic Commerce Platforms," Proceedings of International Conference on Emerging Technologies and Intelligent Systems, pp. 371–380, Aug. 2021, doi: 10.1007/978-3-030-82616-1_32.
[75]. M. R. Khodoomi, M. Seif, and T. Hanne, "Effects and challenges of the COVID-19 pandemic in supply chain management: a text analytics approach," Supply Chain Forum: An International Journal, vol. 25, no. 4, pp. 486–503, Oct. 2023, doi: 10.1080/16258312.2023.2253523.
[76]. K. Suto, H. Nishiyama, N. Kato, T. Nakachi, T. Fujii, and A. Takahara, "THUP: A P2P Network Robust to Churn and DoS Attack Based on Bimodal Degree Distribution," IEEE Journal on Selected Areas in Communications, vol. 31, no. 9, pp. 247–256, Sep. 2013, doi: 10.1109/jsac.2013.sup.0513022.
[77]. H. Yu, M. Kaminsky, P. B. Gibbons, and A. D. Flaxman, "SybilGuard: Defending Against Sybil Attacks via Social Networks," IEEE/ACM Transactions on Networking, vol. 16, no. 3, pp. 576–589, Jun. 2008, doi: 10.1109/tnet.2008.923723.
[78]. A. S. Alqahtani, K. A. Abuhasel, and M. Alquraish, "A Novel Decentralized Analytical Methodology for Cyber Physical Networks Attack Detection," Wireless Personal Communications, vol. 127, no. 2, pp. 1705–1716, Jul. 2021, doi: 10.1007/s11277-021-08716-5.
[79]. A. Gupta, D. Malhotra, and L. K. Awasthi, "NeighborTrust: A trust-based scheme for countering Distributed Denial-of-Service attacks in P2P networks," 2008 16th IEEE International Conference on Networks, pp. 1–6, Dec. 2008, doi: 10.1109/icon.2008.4772644.
[80]. L. L. Biehl, L. Zhao, C. X. Song, and C. G. Panza, "Cyberinfrastructure for the collaborative development of U2U decision support tools," Climate Risk Management, vol. 15, pp. 90–108, 2017, doi: 10.1016/j.crm.2016.10.003.
[81]. A. Pinyo, A. Bangviwat, C. Menke, and A. Monti, "Decentralized P2P Electricity Trading Model for Thailand," Sensors, vol. 21, no. 21, p. 7413, Nov. 2021, doi: 10.3390/s21217413.
[82]. S. J. Leal and M. Napoletano, "Market stability vs. market resilience: Regulatory policies experiments in an agent-based model with low- and high-frequency trading," Journal of Economic Behavior & Organization, vol. 157, pp. 15–41, Jan. 2019, doi: 10.1016/j.jebo.2017.04.013.
[83]. C. Liu and Z. Li, "Comparison of Centralized and Peer-to-Peer Decentralized Market Designs for Community Markets," IEEE Transactions on Industry Applications, vol. 58, no. 1, pp. 67–77, Jan. 2022, doi: 10.1109/tia.2021.3119559.
[84]. R. E. Kranton, "Reciprocal Exchange: A Self-Sustaining System," JSTOR, vol. 86, no. 4, pp. 830–851, Sep. 1996, [Online]. Available: https://dukespace.lib.duke.edu/dspace/handle/10161/1732

**Publisher's note**: The publisher remains neutral with regard to jurisdictional claims in published maps and institutional affiliations. The content is solely the responsibility of the authors and does not necessarily reflect the views of the publisher.

ISSN: 3080-7484