Perfectly Secure Communication, based on Graph-Topological Addressing in Unique-Neighborhood Networks

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Abstract
We consider network graphs \( G = (V, E) \) in which adjacent nodes share common secrets. In this setting, certain techniques for perfect end-to-end security (in the sense of confidentiality, authenticity (implying integrity) and availability, i.e., CIA+) can be made applicable without end-to-end shared secrets and without computational intractability assumptions. To this end, we introduce and study the concept of a unique-neighborhood network, in which nodes are uniquely identifiable upon their graph-topological neighborhood. While the concept is motivated by authentication, it may enjoy wider applicability as being a technology-agnostic (yet topology aware) form of addressing nodes in a network.

1 Introduction
Let a network be given as an undirected graph \( G = (V, E) \), in which node adjacency \( \{u, v\} \in E \) is characterized by two nodes \( u \) and \( v \) sharing a common secret (key). Consider the following question:

Can any two nodes \( u, v \in V \), which are not adjacent (i.e., \( \{u, v\} \notin E \)) exchange messages with computationally unconditional privacy, authenticity and reliability?

By its formulation, an answer cannot use any complexity-theoretic intractability assumptions, thus ruling out public-key cryptographic techniques. Availability is typically a matter of redundancy, and it is known that both, unconditional privacy and availability are both achievable by certain graph connectivity properties and Multipath transmission (MPT) based on secret sharing [10]. In the simplest yet provably most efficient setting [11], Alice sends a message \( m \) to Bob according to the following scheme:

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1. Alice encodes $m$ into a set $s_1, \ldots, s_k$ shares, so that any $d$ out of these $k$ shares suffice to reconstruct the message, while no set of less than $d$ shares leaks any information about $m$. This is a standard application of polynomial $(d, k)$-threshold secret sharing [9].

2. Alice chooses a set of $k$ node-disjoint paths $\pi_1, \ldots, \pi_k$ from her node to Bob. Herein, two paths $\pi_i, \pi_j$ are said to be node-disjoint, if they satisfy $V(\pi_1) \cap V(\pi_2) = \{\text{Alice, Bob}\}$, where $V(\pi)$ is the vertex set of the path. That is, any two paths intersect nowhere in $G$ except at the end-points.

3. Bob reconstructs the secret as usual for polynomial secret sharing, potentially recovering from up to $\lfloor (k - d)/2 \rfloor$ errors. This recovery is possible by the Welch-Berlekamp algorithm [2], exploiting the known “isomorphy” between polynomial secret sharing and Reed-Solomon encoding [5].

This form of MPT achieves confidentiality against any attacker being able to sniff on $< d$ nodes, by design of the secret sharing. Reliability of the transmission follows from the error correction capability of the sharing treated as an error-correcting code. Note that this protocol does not need any point-to-point encryption, if the attacker is constrained to eavesdrop on nodes only, and on strictly less than $d$ of them. This is what we shall assume w.l.o.g. throughout the paper.

The obstacle towards practical implementations of this scheme is the network needing to provide $k$ node-disjoint paths. This property is, by a Theorem of H. Whitney [3, Thm. 5.17] equivalent to $k$-vertex-connectivity of $G$: a graph $G = (V, E)$ is $k$-connected (more specifically $k$-vertex-connected), if it takes at least $k$ nodes to be removed from $G$ until the graph becomes disconnected. That is, Alice and Bob cannot be disconnected by removing up to any $k - 1$ nodes between them. Whitney’s theorem equates this condition to the existence of $k$ node-disjoint paths between Alice and Bob. While this is a strong connectivity requirement in general, 2-connectivity is a highly common feature of networks for the sake of resilience against single node failures. The general problem of extending a graph into $k$-connectedness is computationally intractable [7], but the construction of large $k$-connected graphs from smaller ones is inductively easy [6]:

1. Start with the $\subseteq$-smallest\(^2\) $k$-connected graph, which is the complete graph $K_{k+1}$.

2. Given any two $k$-connected graphs $G_1 = (V_1, E_1), G_2 = (V_2, E_2)$, pick $k$ nodes from each graph, denoted as $u_1, \ldots, u_k \in V_1$ and $v_1, \ldots, v_k \in G_2$,

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1The case of an attacker being able to listen on all the lines in a network requires point-to-point encryption, which, for unconditional security, would call for additional techniques like quantum key distribution protocols (e.g., BB84 [1]) in the network. We leave such technological extensions aside in this work, and shall remain independent of any such assumptions in stating that shared secrets just “exist”, without adopting any prescriptions on how this is practically done.

2Herein, the subgraph relation $G_1 \subseteq G_2$ between two graphs $G_1 = (V_1, E_1), G_2 = (V_2, E_2)$ holds if $V_1 \subseteq V_2$ and $E_1 \subseteq E_2$. 

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and form the connected graph $H = (V_1 \cup V_2, E_1 \cup E_2 \cup \{(u_i, v_i) : i = 1, \ldots, k\})$. Then $H$ is again $k$-connected.

Thus, if the network is to be constructed from scratch in a hierarchical fashion, maintaining it $k$-connected is a simple matter of proper connections between subnetworks into the bigger network.

Authenticity is a different story, but achievable along similar lines: Multipath authentication (MPA) resembles the common form of how handwritten signatures are verified in companies. Departments typically maintain samples of the handwritten signature of a decision maker to verify it on paper documents (otherwise, anyone could just scrawl some name and claim it to be someone else’s handwritten signature). The digital version of this procedure uses the point-to-point shared secrets to mimic a “signature” by a conventional Message authentication code (MAC). Specifically, if Alice’s node $v$ has a neighbor set $\text{nb}(v) = \{w \in V : \{v, w\} \in E\}$, and shares a key $s_i$ with each neighbor $i \in \text{nb}(v)$.

She can use these to undersign a message using a set of MACs under the keys $s_1, \ldots, s_k$ for $k \leq |\text{nb}(\text{Alice})|$. Bob, upon reception of the MACs, can ask Alice’s neighbors for verification, and properly react upon their replies (along node-disjoint paths again). This protocol is depicted in Figure 1 and, using techniques of game theory and universal hashing for the functions $\text{MAC}$ and $h$, is provably secure without any computational intractability assumptions [8]. It must be noted that the vertex-connectivity number $k$ of the graph needs not be equal to the number of neighbors or paths used; it must only be large enough to admit the sought number of neighbors/paths. As such, the number (here $k$) of paths can be less than the vertex-connectivity number of the graph (also denoted as $k$ here).

The remaining question concerns the uniqueness of Bob in being the “signer”
of the message in the MPA scheme. Is it only Alice that could have attached the $MAC$ set $\{MAC(h(m), s_i) : i \in \text{nb}(Alice)\}$? Apparently so, if the neighborhood of Alice uniquely characterizes, resp. distinguishes, her from all other nodes in the network. This, however, is a nontrivial property of a graph, and in the center of study in this work hereafter.

2 Problem Statement

We study the problem of characterizing a node $v \in V$ based only on its graph-topological neighborhood, i.e., we are interested in graphs with the following property:

Definition 1 (Unique-Neighborhood Network). A graph $G = (V, E)$ is a weak Unique-neighborhood network (wUNN), if the mapping $v \in V \mapsto \text{nb}(v) := \{w : \{v, w\} \in E\}$ is injective. We call it a (strong) Unique-neighborhood network (UNN), if no neighborhood is a subset of another node's neighborhood. That is, for every $v$, there is some $u \in \text{nb}(v)$ with $u \notin \text{nb}(w)$ for all $w \neq v$.

The existence of such graphs is immediate by simple examples, such as lines (Figure 2a), circles, or the complete graph. The property, however, may arise or vanish upon adding edges. For instance, the graph in Figure 2c is a wUNN but loses this property upon adding the edge $\{2, 4\}$ to it, as in Figure 2d. It regains unique-neighborhoods, however, when the edges $\{1, 3\}$ and $\{2, 4\}$ are added (Figure 2b).

The distinction between weak and (strong) UNN is necessary because the latter lend themselves better to authentication matters: looking at the graph in Figure 2c node 2 has neighbor set $\{1\}$ which is contained in the neighborhood $\{1, 3\}$ of node 4 as well, so node 4 could use a subset of its neighbors to mimic being node 2, based on neighbor sets (only). Likewise, node 1 could pretend being node 3, because it has, among others, also the neighbors that node 3 knows, and could use those nodes for impersonating 3. Node 3, in turn, could not do this, as long as 1 uses its full neighbor set of authentication. This possibility vanishes if no neighborhood is a strict subset of another neighborhood.

3 An Sufficient Algebraic Condition for UNN

Hereafter, let $n = |V|$ be the number of nodes in $G$. Let $A \in \{0, 1\}^{n \times n}$ be the graph’s adjacency matrix, with $a_{ij} = 1$ whenever node $i$ is connected to node $j$ and zero otherwise. Each row/column of the matrix thus corresponds to a node, and the $i$-th row in $A$ can be taken as a vector of indicators, describing the neighbourhood of node $i$. Likewise, since $G$ is undirected and $A$ is hence symmetric, the same goes for the columns of $A$.

Furthermore, since we are considering UNN for matters of authentication, we assume the graph to have no loops (which would correspond to a party self-certifying the validity of its own MAC), no multi-edges (as the connection as
such counts, not how many cables connect two instances), and to be connected (as isolated nodes could not communicate and hence have no need for authentication). Thus, we hereafter consider graphs that are simple, i.e., without loops or multi-edges, and connected. Since we also consider lines for bidirectional communication (necessarily for the protocol above to work), we do not consider directed graphs hereafter.

A UNN has pairwise distinct rows/columns, so it is conceptually straightforward to sort the rows of $A$ in any order, and to look for adjacent identical rows. While the problem is algorithmically easy, we can also give an algebraic condition to induce the UNN property. Several sufficient conditions are immediate to imply distinct rows, such as full rank of the adjacency matrix $A$, or the matrix being orthogonal. Those, however, is also necessary, so these are overly strong for our purposes.

In a more direct approach, we can directly ask for pairwise distinctness, and it turns out that this is easy to cast into an algebraic condition: let $x_i$ be the $i$-th row of the adjacency matrix $A$. Consider the $ij$-th entry $a_{ij}^{(2)}$ in $A \cdot A^T = A^2$ (the bracketed superscript in $a_{ij}^{(2)}$ shall be a reminder that we indeed do not just

![Figure 2: Examples](image-url)
square \( a_{ij} \), since actually \( a_{ij}^{(2)} = \sum_{k=1}^{n} a_{ik}a_{kj} = x_i^T x_j \).

If \( i \neq j \), then two cases are possible:

1. if \( x_i = x_j \), then we can write \( a_{ij}^{(2)} = x_i^T x_i \)

2. Otherwise, if \( x_i \neq x_j \), then the sum giving \( x_i^T x_j \) will be such that at least one 1-entry in \( x_i \) “matches” with a 0-entry in \( x_j \) (or vice versa), since otherwise, the two vectors would be identical. Thus, the sum \( x_i^T x_j \) must be strictly less than \( x_i^T x_i \) by at least 1, since by the strong \textbf{UNN} condition, there must be a neighbor \( k \) of node \( i \) that node \( j \) does not have, hence the 1-entry at position \( k \) in \( x_i \) hits a zero entry in the same position in \( x_j \), and vice versa. Hence, \( x_i^T x_j < \|x_i\|_1 \) and also \( x_j^T x_j < \|x_j\|_1 \).

Now, look into the first row of \( A^2 = A^T A = AA^T \): in this row, we have all scalar products \( x_i^T x_i \), for which the result is always \( \leq x_i^T x_i \), with equality if and only if \( x_i = x_1 \). That is, we can test for another copy of \( x_1 \) to exist by looking if all entries are less than the first. This is already half the test: the matrix \( A \) has pairwise distinct rows if and only if the diagonal element in the \( i \)-th row of \( A^2 \) is strictly greater than all other elements in that row (likewise, column).

We can convert this into an algebraic inequality condition: write \( 1_{n \times m} \) to mean the \((n \times m)\)-matrix of all 1-entries, and observe that \( x_i^T x_i = x_i^T 1_{n \times 1} \). Thus, we can create the diagonal entry in \( A^2 \) alternatively by multiplying with a vector of all 1es. Extending this idea, note that the entry \( x_i^T x_i \) appears in all columns along the \( i \)-th row in \( A \cdot 1_{n \times n} \). Our condition asks for the diagonal to be strictly larger than the other elements in the same row, and all we have left to do “artificially increase” the actual diagonal by 1 so that the < condition holds there too (otherwise we would have equality).

Overall, we end up with the following sufficient condition:

Theorem 1. A simple graph \( G = (V, E) \) with \( n = |V| \) nodes is a \textbf{UNN} if its adjacency matrix \( A \) satisfies

\[
A \cdot 1_{n \times n} + I_n - A^2 \geq 1_{n \times n},
\]

where \( I_n \) is the \( n \)-th identity matrix and the inequality holds per element.

A similar condition can be obtained for weak \textbf{UNN} only considering that some node \( i \) may have a neighbor set that covers that of another node \( j \). Like above, consider the product \( x_i \cdot x_j \), and let \( \text{nb}(i) \subseteq \text{nb}(j) \), then the 1es in \( x_i \) all match with 1es in \( x_j \), since for a few more 1-entries that \( x_j \) may have. Hence, \( x_i^T x_j = x_i^T x_i \), since all of \( i \)'s neighbors go into the count (as \( x_j \) has a 1-entry for every 1-entry in \( x_i \)). Conversely, \( x_j \) will have a neighbor \( k \) that is not counted upon multiplying with \( x_i \), since \( k \notin \text{nb}(i) \), and therefore we have \( x_j^T x_j < x_i^T x_j \). The two neighborhoods are thus distinct if and only if at least one of the two inequalities is strict, or by adding them, \( 2x_j^T x_j < x_i^T x_i + x_j^T x_j \), and equality is only possible if the two vectors are identical, as in that case, \( \text{nb}(i) \subseteq \text{nb}(j) \) and \( \text{nb}(j) \subseteq \text{nb}(i) \) so that the neighborhood is the same.
Constructing optimal networks w.r.t. some cost function $c : \{0, 1\}^{n \times n} \to \mathbb{R}$ on the adjacency matrix is then a matter of constrained nonlinear optimization:

$$\min_{A \in \{0, 1\}^{n \times n}} c(A) \text{ subject to } (1).$$

One instance of (2) could be, for example, looking for the smallest UNN in which a given graph $G$ appears as a subgraph. Conversely, we can look for the largest subgraph inside $G$ that is a UNN. This is done in the next section.

### 4 Construction and Encounter of UNNs

It is highly unlikely that random graphs, e.g., scale-free or others come up as UNNs. Taking the internet as an example of a scale-free topology, just consider an Internet service provider (ISP) with a set of customers. Each customer is typically connected to only one ISP making this node the only and hence non-unique neighborhood of the customer. However, an ISP located in the center of a star topology may consider its customers as a unique neighborhood to another ISP unless the two have identical sets of customers.

Though a graph $G = (V, E)$ may not be a UNN is there perhaps a subgraph $G' = (V', E')$ with $V' \subseteq V, E' \subseteq E$ that is a UNN. A positive answer is reached by looking at trees first. First, let us define the degree of a node $v$ in an undirected graph is the number $|\text{nb}(v)|$.  

**Lemma 1.** Let $G = (V, E)$ be a tree, and let $S$ be the set of all nodes having degree 1 in $G$. Then, all nodes in $V \setminus S$ have unique neighborhoods in (the full graph) $G$.

**Proof.** The nodes in $S$ are all leafs in the tree, and their exclusion leaves the mapping $f : v \mapsto \text{nb}(v)$ restricted to inner nodes only. Consequently, we consider injectivity of $f$ only on the set $V \setminus S$, but with the neighborhood $\text{nb}$ being determined by the full set $V$. For any two inner nodes $u, v$, those may have the same parents, but since $G$ is a tree, they have distinct children, thus making the corresponding neighborhood (composed from parents and children, possibly also from $S$) pairwise distinct. \qed

Lemma 1 is not optimal in the sense that a leaf that is singleton (in the sense of having no “siblings”, i.e., sharing its parent with no other vertex in $G$) can be included, and the graph remains a UNN. More generally, we can even connect any two disjoint UNNs by a single or multiple edges, with the resulting graph again being a UNN.

**Lemma 2.** Let $G_1 = (V_1, E_1), G_2 = (V_2, E_2)$ be UNNs, with $V_1 \cap V_2 = \emptyset$. Select any two distinct nodes $u \in V_1, v \in V_2$ and construct the graph $H = (V_1 \cup V_2, E_1 \cup E_2 \cup \{\{u, v\}\})$. Then, $H$ is a UNN.

**Proof.** Since we connect a node $u \in V_1$ to $v \in V_2$ (only), the neighborhoods of both are just extended by the other. But since neither node appears in the other
graph, the neighborhoods remain distinct. The remaining nodes that were not involved in the connection between \(G_1, G_2\) retain their neighborhoods as they were, which are again unique since the graphs were vertex-disjoint.

Unfortunately, Lemma 2 does not lend itself to a greedy construction algorithm for a node- or edge-minimal UNN since the property is non-monotone in terms of the subgraph relation, as the example graphs in Figure 2 show. Thus, the set of all UNNs does not form a matroid. Given two UNNs, we can connect them with a single edge to form one graph that is a UNN, and from that point onwards add edges to \(H\), as long as condition (1) on the adjacency matrix tells that we retain a UNN.

More interesting for our purposes is the corollary from these results:

**Corollary 1.** Every undirected graph \(G = (V, E)\) has a vertex-maximal subgraph \(G' = (V', E')\) that is a UNN, and which only excludes nodes (if any) of degree 1 in \(G\).

**Proof.** Take \(T = (V_T, E_T)\) as any spanning tree in \(G\), then Lemma 1 tells that every inner node of \(T\) has unique neighborhoods. Let \(V^o_T\) be the set of inner nodes in \(T\), and let \(E' = (V^o_T \times V^o_T) \cap E\) be the induced edge set. Let \(v \in V^o_T\) be an arbitrary node for which all \(u \in \text{nb}(v)\) have degree 1. That is, \(v\) is a(ny) node that is directly connected to leaf nodes in \(T\). For each such node \(v\), we can pick exactly one of its children \(c \in V_T\) (a leaf) arbitrarily, and add the edge \(\{v, c\}\) to \(E'\). By Lemma 2 the so-extended tree remains a UNN. Moreover, it is a vertex-maximal such subgraph, since adding any further leaf node connected to some \(v \in V^o_T\), we would end up with two children \(c_1, c_2\) of \(v\) whose common neighborhood is \(\{v\}\). Since \(T\) was spanning, there are no other nodes that we could add.

Obviously by construction, Corollary 1 only assures a UNN subgraph of “minimal” vertex-connectivity as being a tree. To construct a \(k\)-connected UNN, Corollary 1 is apparently not very useful as the inner UNN is only 1-connected. Its primary applicability is rather to provide a starting point for optimization like in (2): if \(G\) is not a UNN we can pick a maximal subgraph of \(G\) that is a UNN and keep adding edges (from \(G\) or new ones), until \(G\) has been extended into the “smallest” UNN that covers \(G\).

### 5 Graph-Topological Addressing and Security

The existence of a vertex-maximal subgraph being a UNN is not at all surprising, but the important fact is that the network is a UNN until the “last mile” to the customer, who typically is a node of degree 1. Routing messages into such nodes, however, makes sense only if the node itself is already the receiver, so the actual addressing is only needed until the hop right before the final node. Once this butlast node has been reached, the final point-to-point connection needs no further addressing.
Corollary 1 is thus the final key to “technology agnostic addressing” in the sense as we look for: let $G = (V, E)$ be any network that is not necessarily a UNN. Within $G$, we can construct a minimal spanning tree (by known algorithms), which relative to the entire network $G$ is already a UNN. All nodes outside this UNN are excluded only for sharing a common connection point into the UNN $T$. Now, consider the nodes in $T$ as ISPs, arranged in some hierarchical structure that the tree reflects, then the nodes outside $T$ are all customers connected to the same ISP, but these are directly reachable from their individual ISP node. Thus, the only nodes with a non-unique neighborhoods are the ISP’s customers, while within the larger (inter)net, nodes can be addressed purely using their localities.

The addressing of nodes based on their neighborhoods is agnostic of technology, but in the same degree needs to be aware of topology. As such it may not be applicable in certain specialized domains such as on-chip networks or ad hoc networks. The main area of application are hence fixed network installations such as those maintained by ISPs.

This technological/graph-topological effort comes with a significant practical advantage from the perspective of usable security: it requires key-management in the sense of exchanging common secrets, only between a considerably small number of nodes. Precisely, while symmetric end-to-end encryption in a network of $n$ nodes would require $O(n^2)$ keys to be exchanged, multipath schemes as described here require only $|E|$ such keys to be shared between direct neighbors, while still providing end-to-end security without computational intractability. More important from a practical perspective is the fact that the key-management does not need to rest with Alice or Bob as users: unlike public-key encryption that relies on complex certificate management that to a wide extent runs on the application layer (and hence is in Alice and Bob’s direct hands), multipath transmission and UNN maintenance (i.e., establishment, broadcast and updates to neighborhoods) can run entirely below the application layer, thus providing addressing and confidentiality in a technology agnostic form and completely transparent for all users. Especially matters of maintaining a UNN are flexible and do not need to take into account the entire network topology: an implicit point made in the proof of Corollary 1 is the fact that we do not need all graph-topological neighbors, while it suffices to include only a selection of them to define unique neighborhoods. This also extends to the key-management: for MPA it is only necessary to share keys with the neighbors relevant for the addressing, but not with all neighbors that may physically exist. Thus, the lot of key material maintained by the network additionally shrinks, since the “inner” UNN is merely a spanning tree inside the actual network, on which shared keys are required. Since a tree with $n$ nodes has $m = n - 1$ edges, we end up with $O(n)$ keys necessary for confidential and authentic end-to-end security, as opposed to $O(n^2)$ in the conventional setting of symmetric encryption.
6 Discussion

Multipath transmission schemes in [UNN]s offer the remarkable possibility of doing something like public-key cryptography without public-key cryptography: the sender Alice can send an authentic and confidential message to Bob, with both properties provably implied by graph-topological features only, and not resting on (unproven) computational intractability. Moreover, Alice and Bob use only publicly available information for that purpose, with all matters of symmetric cryptography being handled below the application layer (thus, the crypto is entirely transparent). Unlike computational intractability, an [ISP] can easily assure these conditions to hold in a publicly verifiable manner, and without bothering its customers Alice or Bob with any key-management at all. This may especially be interesting in emerging networks such like the internet-of-things [IoT].

This note leaves a set of problems open for future research, such as properties and complexity of the optimization problem [2], and practical (algorithmic) matters of routing. For ad hoc networks, it is interesting to compute the likelihood of a random graph to be a [UNN]. This property will not necessarily emerge suddenly unlike other graph properties, due to lack of monotonicity. However, the non-monotonicity in connection with the application in the [IoT] and ad hoc networking may render [UNN] interesting objects to study in the context of random graphs.

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**UNN** Unique-neighborhood network

**wUNN** weak Unique-neighborhood network

**ISP** Internet service provider

**MPT** Multipath transmission

**MPA** Multipath authentication

**MAC** Message authentication code

**IoT** internet-of-things