Cooperative Quantum Key Distribution for Cooperative Service-Message Passing in Vehicular Ad Hoc Networks

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ABSTRACT

Secure message transmission in Vehicular Ad Hoc Networks (VANETs) is a challenging task due to its highly dynamic nature. In VANETs, road side unit (RSU) transmits different types of service messages to those vehicles, who have subscribed for that type of message. Intermediate vehicles, those are not subscribed to that service may also receive the message due to broadcast nature of wireless medium. Current literature on VANETs use conventional cryptography for secure message transmission. In this study, the secure service message delivery in VANETs is modeled as a cooperative quantum key distribution among nodes. In the proposed model, vehicles are interested in using services, that are provided by service providers (SPs) through RSUs after a vehicle registered for that service. A quantum key is distributed to registered vehicle through RSU, which is needed to unlock the service. RSU can transmit the quantum key to the vehicles, which are within its transmission range. A cooperative vehicle helps RSU to transmit the quantum key to a vehicle that is not in its transmission range. A network formation game is modeled for the proposed problem between RSUs and vehicles to form network tree. Vehicles (nodes) use services, work as relay node in-order to cooperate with RSU to relay quantum key. In this paper, a distributed algorithm for cooperative quantum key distribution in VANETs (CQKDVN) is modeled, which helps RSU's to choose a suitable relay node for quantum key distribution. The proposed algorithm, CQKDVN, helps nodes to decide whether to cooperate with a RSU or not based on the incentive it receives by serving a RSU to deliver quantum key to a destination node. CQKDVN also helps the RSU to adapt to the network topology changes such as a node move out of its range or movement of relay nodes that triggers to switch to a new relay node. CQKDVN constitute the network topology into a Nash network.

Keywords:

VANETs, Quantum key distribution, Cooperative communication, Network formation game

1. INTRODUCTION

In VANETs vehicles form a network by communicating among themselves to provide safety and comforts to the passengers [2, 7]. Vehicles communicates with RSUs to access Internet and other services like news, weather report, shop, game, communicating with other vehicles, road and traffic conditions and likes. Vehicles have to register with the SP in order to use a specific service. Once the vehicle register for a particular service, the SP issue it a secure key. That service can be used through that particular key only, to ensure that only the vehicle registered with the SP can access the service. Current literature uses conventional cryptography techniques to provide protection [10, 17] which do not provide enough protection in cooperative vehicular environment. This paper presents quantum based cryptography in cooperative vehicular environment to provide utmost security. Cooperative communication in VANETs solve intermittent connectivity problem which occurs due to varying relative speed of vehicles, multi-path fading or interference [11, 20]. In cooperative communication neighboring nodes helps in the communication by over-hear messages of ongoing communication and store them for future use or relay messages to other nodes [9, 14, 15]. The performance of cooperative communication technique, to a great extent, rely on the process of cooperative node selection [16].
Existing literature on VANETs use conventional security [6]. Cooperative communication is also used to improve the performance of VANET [16]. In this study, cooperative quantum key distribution is used to provide security in cooperative communication in VANETs. The network formation game [12] framework is used to select suitable relay node for quantum key distribution.

1.1 Contributions

The main contribution of this paper is to propose a distributed model for cooperative quantum key distribution for service message sharing problem in VANETs. Another key contribution of this paper is to transmit the quantum key securely to the authorized node with the help of cooperative relay node. This paper uses network formation game [12] to select suitable relay node for quantum key distribution of a service message. The proposed model, CQKDVN, study that nodes subscribe with SPs in order to access desired services through RSUs and use the service by a secret key provided by SP. RSU forms coalition with a cooperative node which may work as a relay node for that RSU to transmit the quantum key to the desired node. A relay node may cooperate with the RSU node and forms coalition with it based on the incentive it receives, which is calculated by the distributed algorithm running on the node. The distributed algorithm running on each node calculates the incentive based on the successful transmission of key bits of a particular service to the destination node versus the key bits lost in relaying. A cooperative node can relay key of one type of service to a destination node at a specific time, and can change the coalition with the destination node if other coalition provide it with better incentives than the previous one. In this study, network formation game [12] is used for relay node selection by RSUs. The relay selection problem for the quantum key distribution to the destination node is modeled as a network formation game between RSUs and the cooperative neighboring nodes of a RSU. The distributed algorithm runs on each node by CQKDVN and always converges to a Nash network [12, 13]. This paper explained that the CQKDVN can automatically adjust the network topology to the environmental changes for instances, destination node moves out of the transmission range of RSU, relay node creates coalition with RSU, relay node changes the coalition, relay nodes moves out of the transmission range of RSU, and relay node cheats by using the key by itself and sending wrong key to the destination node. The contributions of the paper can be summarize as follows:

(1) Secure service-message sharing in VANETs using quantum key distribution
(2) Quantum key distribution using cooperative relay node
(3) Detect the cooperative relay node which tries to access the key itself
(4) A network formation game framework is used in cooperative relay node selection

The paper is structured in the subsequent sections. Related works in relevant topics are reviewed in Section II. The system model is proposed in Section III. In Section IV, the relay selection for quantum key distribution of service-message problem is modeled as a network formation game. The conclusion is drawn in Section V.

2. RELATED WORK

Bennett et al. [1] proposed a quantum key distribution protocol to transmit a key from source to destination.
Cheng et al. [3] proposed wireless communication with quantum communication. Cheng et al. also proposed a quantum routing protocol for the quantum wireless communication networks [3]. A novel wireless communication protocol is proposed with a hierarchical network architecture in the paper to implement quantum routing in wireless communication. Yu Xu-Tao et al. [19] proposed quantum communication in distributed wireless network. Yu Xu-Tao et al. also introduced a routing protocol along with quantum information transfer protocol in distributed wireless network. However, these literatures have not discussed the problem of sending the polarized photon as quantum bits (qubits) using the cooperative relay nodes.
Saad et al. [12] also propose a network formation game for wireless networks. But security has not been addressed in the literature so far.

3. SYSTEM MODEL

A node communicates with RSU to subscribe for a service. RSU transmits quantum key to the node when it is within its transmission range. RSU transmits qubits to the destination node through cooperative relay nodes when the destination node moves out of the transmission range of the RSU. Let us consider a vehicular with $R = 1, 2, ..., R$ RSU nodes, $N = 1, 2, ..., N$ vehicular node, and a total $S = 1, 2, ..., S$ service messages are provided by SPs. Service message $s_l \in S$ is different from $s_{l+1} \in S$, in other words they are different from one another. A SP, can provide many services, but all are distinguished from one another. A node n_k subscribe for a service s_l through a RSU r_i. RSU r_i then transmits the quantum key to the node n_k through which it can access the service. The nodes may moves out of the transmission range of the RSU r_i which is transmitting the quantum key to it. In that situation, a neighboring node n_j, which is in the transmission range of the RSU and has node n_k within its communication range, works as relay to transmit qubits. The quantum key consists of a predefined set of bits $Q = 1, 2, ..., Q$, which is set to 100 in this study.
In this paper, it is assumed that, both RSUs and nodes are equipped with two types of communication techniques, one is the conventional wireless communication technique used in VANETs and the other one is the quantum communication technique. Quantum key is transmitted over quantum channel, which is air in the presented case, through quantum communication technique. It is also assumed that both wireless communication and quantum communication can take place at the same point of time, without disturbing one another. This paper considers that the loss of qubits happens, when the node move out of the transmission range of the transmitter RSU or due to the effects of the network topology. Apart from these two cases, the RSU will successfully transmits the qubits with 100% probability and qubits losses due to other reasons is not considered. The reception rate of qubits by the node n_k can be given by,

$$\bar{R}_{n_k} = \frac{n_k.\beta_b}{\delta_{ik}} \tag{1}$$

where, $\bar{R}_{n_k}$ denotes the reception rate of β_b qubit send by RSU r_i to the node n_k with a delay δ_{ik} occurred in the transmission.
Speed of nodes and their topology effects the quantum communication. The receiving node of the qubits may move away from the transmission range of the RSU at any point of time, which disturb the transmission of qubits. The probability of successful transmission of qubits is given by,

$$\bar{P}^{t-1}_{\beta_b,n_k} = P_{\beta_b,n_k v_k} \prod_{j=2}^{B} P_{n_j v_j} \tag{2}$$

where, $\bar{P}^{t-1}_{\beta_b,n_k}$ is the probability of the successful reception of qubit β_b by node n_k with a velocity v_k in the presence of neighboring nodes B. B is the set of neighboring node $B = 1, 2, ..., B$, where $B \subset N$ with each node $j \in B$ having a velocity of v_j. B is within the transmission range of the RSU r_i.
When the destination node n_k moves out of the transmission range of the RSU node, then a cooperative node n_j helps to transmits the qubits to the destination node n_k. Let C be a set of nodes, $C \subseteq B$ which are in the transmission range of both r_i and n_k. The reception rate of qubits β_b through a relay node n_j, where $n_j \in C$, is given by,

$$R_{n_k} = \frac{n_k.\beta_b}{\delta_{ij}\delta_{jk}} \tag{3}$$

where, R_{n_k} denotes the reception rate of β_b qubit through the relay node n_j from the RSU r_i with a delay δ_{ij} and δ_{jk} incurred in the transmission from node the RSU r_i to the relay node n_j respectively. The probability of successful reception of qubit β_b is given by,

$$P^{t^{-1}}_{\beta_b,n_k} = P_{\beta_b,n_k\upsilon_k} P_{\beta_b,n_j\upsilon_j} \prod_{j=3}^{B} P_{n_l\upsilon_l} \tag{4}$$

where, $P^{t^{-1}}_{\beta_b,n_k}$ is the probability of the successful reception of qubit β_b by node n_k with a velocity υ_k through a relay node n_j with a velocity υ_j in the presence of neighboring nodes B.
The RSU node transmits the qubits to the destination node with a reception rate of $\bar{R}_{n_k}$ and with the probability $\bar{P}^{t^{-1}}_{\beta_b,n_k}$, when it is within its transmission range. When the destination node moves out of the range of the RSU, then it transmits qubits through a relay node with a reception rate of R_{n_k} and with the probability $P^{t^{-1}}_{\beta_b,n_k}$. In this work, the model restricts itself using more than one relay node.

4. NETWORK FORMATION GAME

4.1 CQKVN

In quantum key distribution the key is transferred as photons and the polarization of photon represents as the "0" or "1" bit [8]. In conventional communication an eavesdropper can capture an ongoing communication detect the bit and regenerate it. While in the case of quantum communication, as the no cloning theorem [5, 18] states that, it is not possible to duplicate a photon. Hence, quantum communication is more secure than its conventional counter part. According to the BB84 protocol [1], RSU transmits a polarized photon by choosing a basis, either rectilinear or diagonal, to the destination node. The destination node use an analyzer, either rectilinear or diagonal, to detect the qubits. Later the destination node communicates with the RSU and reveal its choice of basis over classical wireless channel. RSU tells the destination node which of the bases are correct and check some of the bits from the correct set. If the error rate is less than 25% then the key is used for future communication over the wireless channel. In VANETs, due to the dynamic nature of vehicles, the RSU node may not get enough time to transmit the key over quantum channel to the node that has subscribed for a service message. In this scenario one can not apply the BB84 protocol. In this study, a cooperative Cooperative Quantum Key Distribution for Cooperative Service-Message Passing in VANETs is proposed, which use a relay node to transmit the quantum key to the destination node. The RSU node send polarized photon to the relay node. The relay node use an analyzer, rectilinear or diagonal base, to detect the polarization of the photon. After detecting the photon the relay node transmit a new photon with the detected polarization to the destination node. The destination node upon receiving the polarized photon, choose a random analyzer, rectilinear or diagonal, to detect the polarization of the photon. The destination node, after receiving all the quantum key, send it's choice of base for each bit to the RSU node. The relay nodes also inform the RSU node about their choice of base after it transmit polarized photon to the destination node.
The COQKD protocol presented in this paper, introduce the security of quantum key distribution in VANETs for service-message accessing securely by nodes. When RSU transmits quantum key directly to the destination node, the communication is the most secure. But, when the RSU node use a relay node to deliver the quantum key, the key is reveled to the relay node. In order to solve the above mentioned problem, the RSU deliver 25% of the quantum key to directly to the destination node and the rest 75% key may be send through relay node. Therefore, even if a single relay node deliver the total 75% of the key, it will not have the full key to access the service message. A relay node is selected among the cooperative nodes based on a hedonic coalition game, which is discussed in the following subsection.

Property 1 When a polarized photon passes through a polarizer it acquires the polarization of the polarizer and the resultant intensity is calculated using the law of Malus, $I = I_0 cos^2\theta$.
where, I_0 is the original intensity of the light and θ is the angular difference between the polarized light and the polarizer.

Definition 1 RSU sends qubit to the destination node, and the destination node receives the qubits with their choice of basis.
RSU sends qubit or polarized photon to the destination node. Destination node use either rectilinear or diagonal basis (or polarizer) to receive the qubit. If the choice of basis by the destination node is correct then it receives the correct qubit.

Definition 2 RSU searches for relay node over conventional wireless channel, when the quantum link between the RSU and the destination node is unavailable.
Due to the dynamic nature of VANETs, network topology change disrupts the quantum link between the RSU and the destination node. RSU selects a cooperative relay node, which has a quantum link with the destination node. A single relay node is selected using the network formation game, discussed in the following Game Formation subsection.

Definition 3 Cooperative relay node receives qubit using their choice of basis, then transmit a polarized qubit that they have receive to the destination node and the choice of basis is informed to the RSU.
The cooperative relay node use its choice of basis to receive the qubit. It then transmit a qubit with the same polarization it has received to the destination node. The cooperative relay node transmits its choice of basis to the RSU after the destination node received the qubit.

Definition 4 Destination node transmits the list of each choice of the basis to the RSU over conventional wireless channel, and the RSU inform the destination node about the correct choice of basis.
The destination node transmits the list of its choice of basis to the RSU after it receives the entire key. RSU informs the destination node which of its choices are correct according to the BB84 protocol.

Definition 5 At least 25% of the key should be directly transmitted to the destination node by the RSU.
RSU must send at least 25% of the key directly to the destination node, so that any cooperative relay node should not have significant amount of key to gauss the original key.

Theorem 1 . Relay node can not determine the entire key with the help of the subset of the key they transmitted.

Proof: . Destination node sends their choices of basis at the end of the entire key reception. Which makes difficult for a cooperative relay node to determine the location of the qubit, that they have transmitted in the key. RSU transmits 25% of the key directly to the destination node, which makes it impossible for the cooperative relay nodes to predict the whole key, which proves the **Theorem 1**.
In the following subsection Network Formation Game framework is used to counter the problem of dynamic topology changes of VANETs, and to select the best cooperative relay node which have the good quantum link with both RSU and the destination node. The Network Formation Game framework proposed in the paper selects the best relay node from the group of relay nodes for the RSU whenever the network topology changes or the quality of

quantum link from the relay node to RSU and destination node changes.

4.2 Game Formation

Let us consider that there are N nodes in the VANET at a given point of time. RSU node N_i transmits qubit directly to the destination node N_j, when the quantum link between them is present. Due to the dynamic nature of VANETs the quantum link between N_i and N_j may disrupt at any point of time. RSU node searches for the relay node N_k, which has a good quantum link to the destination node from the group of relay nodes N_k, where $K = 1, \ldots, N-2$. The main objective here is to formulate a game among the neighboring nodes, to model the cooperative retransmission of qubits to the destination node, such a way that only one of the neighboring node is selected as a relay node. The analytical framework of network formation games is adopted from the work of Saad et al. [12]. A network graph $G(V, E)$ is formed, where V denotes all vertices and E denotes all edges that connect two nodes. The quantum link between two nodes i and j are denoted by q_{ij}, which is the only possible path through which qubits can transfer between two nodes. RSU use following strategies in this network formation game to select a cooperative relay node. Firstly, the relay node k should have a direct quantum link with the destination node. Secondly, the relay node k should have a quantum link with the RSU. Thirdly, relay nodes which are traveling in the same direction with the destination node get more priority than others. Lastly, the relay nodes which have less relative speed with the destination node get more priority than other relay nodes. An incentive function is formulated which calculates the received incentives by a relay node. Based on the incentive function, a relay node is selected from the group of cooperative relay nodes, by the RSU.

4.3 Payoff Function

A payoff function has been formulated by the authors, that allocates incentives to relay nodes. The profit is measured by the number of packets successfully transmitted to destination node, direction of the relay node with the destination node, and the cost is calculated in terms of delay induce by transmission, the relative speed of the relay node with the destination node. RSU obtains the incentives of each relay nodes and choose the relay node based on the best incentive received by a relay node. The payoff function calculate incentives with the following equation.

$$\vartheta_i = \begin{cases} \frac{(\Lambda_i . \delta_{i,j})}{\sigma_i . \upsilon_{i,j}}, & \text{if} \quad N > 2 \\ 0, & \text{otherwise} \end{cases} \tag{5}$$

where, Λ_i denotes a packet i successfully transmitted to the destination node j, $\delta_{i,j}$ denotes the direction of the relay node i and destination node j, σ_i represents the delay in transmitting a packet i, and $\upsilon_{i,j}$ denotes the difference of relative speed of relay node with the destination node. N denotes the total number of nodes.
The network formation algorithm runs on each node and continuously calculates the received incentives it may get by serving neighboring nodes. Due to the dynamic nature of VANETs, RSU need the help of a relay node to transmit a qubit to a destination node. RSU then collects the incentives of each neighboring node of that destination node, which the neighboring node may get by serving the neighboring node over conventional wireless channel. Among the collected incentives, the cooperative relay node, that receives the best incentives is selected by the RSU to cooperatively transmit the qubit. The following assumptions are considered to formulate the network formation game among the RSU and the neighboring nodes of the RSU.

(a) RSU transmit qubits to a node. When, the destination node is not within the transmission range of the RSU, then a cooperative relay node, if present, is used to transmit qubits to the destination node.
(b) Cooperative relay nodes continuously calculates the incentive they may receive by serving a neighboring node. RSU obtain the incentive value of each relay node,
(c) RSU broadcast a message, over conventional wireless channel, to all neighboring nodes, which asks the incentives of the nodes which can transmit qubits to a destination node.
(d) RSU choose the best neighboring node as relay node from all neighboring nodes, based on their incentive received and use that node to transit a qubit.
(e) RSUs in the proposed model of network formation game, forms a network graph, select a relay node to the destination node.

The presented network formation algorithm creates network graph, starting with a RSU to a destination node, with the help of a cooperative node when needed. Cooperative nodes always tries to improve their incentives. The proposed payoff function improves the performance of the vehicular network using cooperative communication techniques.

4.4 Algorithm for Network Formation

A network tree is formed, RSU - cooperative relay node (RN) - destination node (DN) when the RSU can not directly transmits a qubit to the destination node, otherwise the network tree is formed only with RSU and the DN with the following properties.
Property 2: RSU forms a directed tree structure with DN when the DN is in quantum communication range by the network formation game proposed in this paper.
Let us consider a network graph G consisting of N nodes with a RSU ($N_i = 1$), a DN ($N_j = 1$), and RNs ($N_k\{k = 1, \ldots, N-2\}$), where RSU connects with a DN according to definition 1. There can be numerous network tree present at any time in VANETs, but a RN can serve one DN at a time.
Property 3: RSU forms a directed tree structure through RN with DN when the DN is not in quantum communication range by the network formation game proposed in this work.
Let us consider a network graph G, where the quantum communication link between RSU and DN disrupts. According to the definition 2, RSU tries to transmit a qubit to the DN through RN, when the quantum communication between RN and DN breaks. RN continuously calculate the incentives they may receive by serving a neighboring node with the equation 5, and always tries to maximize their received incentive.
Let there are total S number of strategies that can be played by a RSU to select the best RN. When the quantum connection with the DN breaks then RSU send request to neighboring nodes. Neighboring nodes, which want to cooperate with the RSU sends their payoff value calculated from the equation 5. RSU sort the cooperative relay nodes with their payoff value.

$$\rho = max \{\vartheta_i \mid i = 1, \ldots, N < 2\} \tag{6}$$

RSU plays the strategy ρ, that achieves the maximum incentive to a RN, which is calculated using the equation 6. The RSU modifies the network graph G to $G + \rho$ by playing the strategy from the set of strategies S. This is called pure strategy. The concept of pure strategy is adapted from the work of Saad et al. [12].

Definition 6: A pure strategy can be defined for a RSU as ρ.

The presented network formation algorithm selects the pure strategy that a RSU take to form the network graph. The network formation algorithm running in RNs continuously calculates the incentive it may receive by serving neighboring nodes. RNs send their respective incentive to serve a particular DN to the RSU when RSU wants it. RSU then selects the best RN which get the best incentive among the RNs and transmits the qubit. The network can converge to a Nash network [4, 12], where RSU can not change the selected RN with another RN which may achieve greater incentive than the previous RN. The concept of Nash network is adapted from the literature of Saad et al. [12].

Algorithm 1 Network Formation Game Algorithm

```
RSU transmits a qubits to DN over quantum channel
while !End of transmission by RSU do
    if No quantum communication link then
        Request(RNs)
        max(RNs)
        Transmit through the selected RN
    end if

end while
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Definition 7: When a RSU can not change a selected RN with another one in the network graph $G(V, E)$, then the network is a Nash network.

The Nash network in a network formation game is equivalent to Nash equilibrium [12].

The proposed network formation algorithm allows RNs to cooperatively transmit a qubit from the RSU to a DN over quantum channel. All RNs continuously calculates the incentive they may receive by serving all neighboring nodes. When RSU ask for incentive value the RNs may get by serving a DN, then all RNs sends their respective incentive value. The RSU then selects the best RN according to their incentive, and transmit the qubit. A network graph G is formed when RSU transmit qubits directly to a DN. Whenever, RSU can not reach the DN over quantum channel, RSU take a pure strategy from its strategy set ρ, and forms a network graph $G + \rho$. Theorem 1 proves that the pure strategy will converge the network graph into a Nash network.

Theorem 2: The initial network graph G converges to a Nash network $\bar{G}$, where RSU can not change its pure strategy to change the selected RN with another RN which achieves more incentives than the previous RN.

Proof: The presented distributed algorithm for network formation game, forms a final network graph $\bar{G}$ from the initial network graph G.

$$G \rightarrow \bar{G} \tag{7}$$

RSU starts the communication by transmitting qubits to a DN and forms a network graph G. RSU transmits qubit to DN through RN, RN_i, when it can not reach the DN directly and forms a network graph $\bar{G}$. Let us assume that there exists another RN, RN_j, which can receive more incentive than RN_i to serve the DN. Equation 6 selects the RN which receives best incentive at that point of time by serving DN. Therefore, RN_j would have selected by the equation 6 if it receives more incentives than the selected RN, RN_i. Hence, it is proved that the network graph $\bar{G}$ formed by the proposed network formation algorithm converges to a Nash network. The network formation algorithm is a distributed algorithm which continuously runs in RNs and RSU independently. Sometimes, there may not be any RN present to help RSU to transmit qubit to DN.

5. CONCLUSION

In this study, a cooperative quantum key distribution technique is proposed to provide security in vehicular communication. In this proposed model, vehicles register with SPs to acquire desired service. A novel model is proposed by the authors that helps the vehicles to securely access messages from SPs in VANETs. SPs transmit a key through RSUs to the vehicles, who wants to access the service, over quantum channel. The key then used to secure all further communications between SP and the vehicles over conventional wireless channel in VANETs. Other vehicles could not decode the message as they do not have the key even though they can access the message due to the inherent broadcast nature of wireless channel. Due to the highly dynamic nature of VANETs it is not possible to maintain the quantum channel between a vehicle and RSU for sufficient amount of time. To overcome this problem, a cooperative quantum key distribution technique is introduced, which modifies the BB84 [1] protocol, to transmit qubits through cooperative relay nodes. Through mathematical analysis authors explained that the proposed cooperative quantum key distribution technique does not reduce the security provided by the BB84 [1] protocol. Cooperative relay node selection is a very important task in this protocol, because network performance depends on it. Network formation game framework is proposed by the authors for the selection of the relay node. The network topology has been analyzed in details and it can be found that network formation will converge to a Nash network.

For future work, the performance of CQKDVN will be evaluated under different network scenarios. The performance of quantum communication in vehicular environment will be tested and how long a quantum channel can survive and the bit error rate of the quantum communication would also be evaluated in future works.

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