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Trusted Cooperation Among Virtual Base Stations in C-RAN

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\textbf{ABSTRACT} Cloud radio access network (C-RAN) has become one of the hot-spot research directions in both industry and academia to facilitate 5G development. Its architecture is mainly divided into three parts: 1) Virtual base station (VBS) pool including a number of base band units that apply for real-time cloud computing technology to carry out digital processing tasks; 2) Remote radio heads (RRH) that are used to collect the wireless signals from all wireless devices; 3) Front-haul network connecting the RRH to the VBS pool. The information of base stations (BS) resides in a centralized VBS pool, multiple operators can allow their VBS pools to exchange control data and cooperate with each other to provide high-quality 5G services. In this process, trustworthy cooperation and platform-trust authentication among multiple mobile operators are required to realize high networking performance and secure 5G environment. However, this topic has been scarcely studies and is still in its infancy. In this paper, we first propose a C-RAN inter-operator cooperation scheme (IOCS) to support the cooperation of multiple operators in C-RAN and allow them to share resources in a trustworthy and secure way based on trusted computing platform. An access trust management pool including VBS trust managers is set up in IOCS to administrate an operator’s VBS pool. It allows an end user to consume other operators’ network resources in a trustworthy manner when its own operator’s network cannot satisfy the quality of service requirements. Furthermore, we design a trusted cooperative platform based on OpenStack to implement IOCS. Performance evaluation and simulation results illustrate the high operation efficiency in IOCS comparing with other schemes. Game theoretical analysis shows the condition of inter-operator cooperation by taking operator trust into concern.

\textbf{INDEX TERMS} Cloud radio access network (C-RAN), trusted computing, trust management, inter-operator cooperation, 5G.

\section{I. INTRODUCTION}

The 4th generation wireless networks are widely used currently; however, they neither offer a big data bandwidth and infinite network capabilities, nor satisfy the increasing demands of both mobile users and mobile network operators. For example, as the capital expenditure (CAPEX) or the operating expenditure (OPEX) cost of a network architecture reaches a high level, more and more mobile network operators focus on the percentage of Total Cost of Ownership (TCO) in the whole network architecture, such as air conditioning costs, base station selection costs, etc. [1], [2].

Cloud Radio Access Network (C-RAN) was proposed to overcome traditional problems in Radio Access Networks (RAN) and satisfy users’ requirements on the next generation mobile communication networks and wireless systems (5G) [4]. As a new centralized architecture based on Software Defined Radio (SDR) networks [3], C-RAN is playing a very important role in a 5G environment (i.e., macro cell, micro cell, pico cell and indoor coverage) due to its mobility, flexibility, easy extension and low TCO. Generally speaking, a C-RAN architecture consists of three parts: i) a centralized Virtual Base Station (VBS) pool, composed
of a number of Base Band Units (BBU), which is applied for real-time cloud computing technologies to carry out digital processing tasks; ii) Remote Radio Heads (RRH) that collect wireless signals from all wireless devices; iii) a front-haul network connecting the RRH to the VBS.

C-RAN holds a number of advantages. First, multiple VBSs are managed together as a whole, connected to many sector antennas that cover a wide area and share signals to minimize the computing-resource management cost. Second, the cooperative processing among base stations achieves the reconstruction of spectrum resources. Third, real-time cloud computing technology can dynamically implement load balancing, process aggregation and reduce inter-cell interference phenomenon. Multiple operators’ VBS pools can collaborate with each other through this new C-RAN architecture to provide affordable, effective and highly efficient 5G services. For example, such a design is expected when an operator’s network services can be provided by other operators’ VBS pools for satisfying the quality requirements of 5G network services when its own BS is busy or overloaded. In this situation, trustworthy cooperation among operators becomes necessary.

A. MOTIVATIONS

When applying the excellent advantages of C-RAN to meet the service demands of 5G, the security and trust issues in C-RAN is an important and interesting topic. In different logical planes (i.e., physical plane, control plane and service plane) of C-RAN, various kinds of attacks [5] exist. For example, in the physical plane, due to the characteristics of C-RAN, it is especially vulnerable to such attacks as eavesdropping attack, jamming attack, impersonation attack, primary user emulation attack (PUEA) and wireless channel threats. The primary attacks in the control plane are Media Access Control (MAC) layer protocol attack and common control channel threats (e.g., MAC spoofing, extended Denial of Service (DoS) attack, jamming attack, etc.). The service plane is the most vulnerable layer among the three planes due to its importance. Such attacks as Transport and Application Layer Protocol Attack, cloud computing security threats, virtualization attack, user privacy threat and other security threats [6] could happen. There are many understudied issues worthy of research and exploration in the field of C-RAN security.

The infrastructures of C-RAN are established by multiple operators. Each of these infrastructures can serve its own users to satisfy their needs based on the referred architecture (centralized or partially centralized). Therefore, one open issue is how to fully employ the existing network resources offered by multiple operators and guarantee the reliability and security in such a cooperation environment under the C-RAN architecture. Moreover, we should ensure different operators’ subscribers to flexibly consume available resources provided by multiple operators in a trusted way. In other words, we should ensure that the VBS pools in different operators and the entire cooperation process among them are reliable and secure. However, how to establish a trustworthy cooperation environment in C-RAN is rarely studied by current literature. Most schemes lack deep research on their applicability [7]–[9]. Therefore, maximizing resource utilization, gaining extra profits and ensuring high-quality networking services while ensuring trustworthy cooperation among operators is a practical issue to be solved.

B. MAIN CONTRIBUTIONS

In this paper, we propose an Inter Operator Cooperation Scheme (IOCS) to support multiple operators to share their resources in a trustworthy and secure way based on Trusted Computing Platform (TCP) technology in the infrastructure of C-RAN [10]–[12]. We also demonstrate how our IOCS can be realized based on OpenStack and virtual Trusted Platform Module (vTPM).

In our scheme, an access trust management pool that contains a number of VBS trust managers (TMs) is established, each of which manages the VBS pool (e.g., spectrum resources, etc.) of one operator. These VBS TMs can issue tokens and provide a number of user configurable Application Programming Interfaces (APIs) to establish a trust-maintenance mechanism among multiple operators. These tokens represent the identity of the VBS Pool, which can help the VBS Pool rent network resources and balance service loads across multiple operators’ VBS pools. Using these APIs, the operators can implement some cooperative strategies to control trust maintenance for achieving trusted cooperation across multiple cellular networks owned by different mobile operators [11]. In particular, one operator can monitor the configuration information of the VBS pool in real time to verify and ensure that another operator’s VBS pool is working as its TM expectation by embedding a trust cooperation strategy into the VBS TM.

Once a VBS pool lacks of networking resources, its own VBS trust manager can send a rental request to other VBS TMs. The other VBS TMs can challenge the trustworthiness of a remote VBS trust manager and make a corresponding response based on an established cooperation strategy by considering essential factors (e.g., renters’ current status of resource consumption, renters’ free resources, rental requests, priority of resource rental, the agreement with the requester, estimated resource demands in a requested period). Next, after comparing the offers from other operators’ TMs, the requester chooses the most suitable one according to its own selection strategy (e.g., reputation of a renter) [12]. Finally, the requester locates the selected VBS Pool to start inter operator cooperation.

We further implement the proposed scheme by developing a trusted cooperative platform based on OpenStack to validate its performance. Performance evaluation and simulation results show that IOCS has highly efficient operation and correct trust attestation. Additionally, we analyze whether the operators would like to collaborate with each other by applying game theory. Specifically, the contributions of this paper can be summarized as below:
• We propose the IOCS to support trustworthy cooperation among operators based on TCP technology in C-RAN. We specify its detailed system structure, trust attestation and cooperation procedure and document it to be with flexibility, secure and trustworthy cooperation, generality and cost economy.
• We implement the IOCS through a trusted cooperative platform based on OpenStack and virtualization technology. The performance test results further show that our scheme offers sound availability, efficiency and effectiveness.
• We apply game theory to analyze the condition of inter-operator cooperation by taking the operator trust into concern.

The rest of the paper is organized as follows. Section II gives a brief overview of related work. In Section III, we introduce the system structure of the IOCS and its trust attestation and cooperation procedure. Section IV presents IOCS implementation, followed by security analysis, performance evaluation and analysis on operator cooperation with game theory. Finally, we conclude our work in the last section.

II. BACKGROUND AND RELATED WORK
In this section, we introduce the technical background of our work and review related work. We first briefly overview security issues and the requirements in C-RAN service plane. Then, we introduce the basic of trusted computing and computing platform integrity measurement, followed by a review on platform attestation and authentication. Finally, we introduce the game theory that will be applied to analyze the possibility and condition of multiple operator cooperation in Section IV.

A. SECURITY ISSUES AND SECURITY REQUIREMENTS OF C-RAN SERVICE PLANE
As one of the key technologies of 5G, C-RAN is expected to solve the challenges faced by traditional wireless access networks [13]. An increasing number of operators start to investigate the C-RAN application scenarios (e.g., macro cell, micro cell, pico cell, indoor coverage system, etc.) and attempt to apply it as an alternative of current cellular networks to support the growing end-user needs in a cost-effective manner.

In 2015, Wu et al. [5] proposed a novel logic structure of C-RAN, which includes physical plane, control plane, and service plane and refines the functional requirements of each layer, service cloud, service-oriented architecture and personal resource scheduling and management. With the development of C-RAN technology, the security of C-RAN architecture is more required than before. However, the main efforts of current C-RAN study only focus energy efficiency, resource allocation, and QoS enhancement. In this part, we leave along the threats and attacks in all the logic structure of C-RAN while mainly concentrate on the service plane and existing solutions to resist them [14]–[17].

The service plane of C-RAN is a service-oriented cloud platform, which directly interacts with the end-users and service providers. The interaction between users and service providers is not transparent. The users just attach importance to whether their requirements are satisfied while do not care who provides that the services. In C-RAN, the service (e.g., real-time data processing, information transmission of terminal devices and special channels, and dynamic traffic capacity allocation, etc.) is provided by the VBS pool. The service plane should prevent the VBS pool from invasion and provide an essential security module for Fine-Grained Access Control (FGAC) and identity authentication, etc. Current security research on the service layer can be divided into the following categories with respect to different kinds of attacks.

1) TRANSPORT AND APPLICATION LAYER PROTOCOL ATTACKS
C-RAN uses relevant protocols like TCP/UDP to provide application delivery services in the transport and application layers, which is similar to traditional wired networks. Thus, such attacks as TCP/UDP flooding attack, sequence number prediction attack, SQL injection, and FTP bounce attack could happen [14]. Corresponding solutions to resist the above attacks work herein.

2) CLOUD COMPUTING SECURITY THREATS
If a malicious user attacks C-RAN platform, the security of the VBS pool will be compromised very easily. Tari et al. [15] summarized the opportunities, solutions, and progress of cloud security and privacy research in recent years and discussed the shortcomings of traditional cryptography in dealing with cloud computing. For a good cloud system environment, the system should store and manage data with security, employ reliable trusted third party and trust management, and support fine-grained access control, and so on. Xiao and Xiao [16] defined the basic security requirements for building a trustworthy cloud platform system; i) outsourcing security which means the cloud platform should present the solutions to security problems in terms of trust authentication, authorization, and protecting privacy through encryption. ii) multi-tenancy security that the common cloud platform should ensure fairness, reasonability and security of resource allocation arrangement when running in a virtual environment. iii) massive data and intense computation security that the cloud system should have new strategies and protocols to ensure the security of massive data and intense computation processes.

3) VIRTUALIZATION THREATS
The traditional base station connects to a certain number of sector antennas that cover a small area and only handle transmission/reception signals in its coverage area. C-RAN gets together dispersive BSs from a VBS pool based on virtualization. In the pool, different BS closely cooperate with each other and efficiently share resources and processing power. Wang et al. [17] summarized four preventive methods...
migrating, its keys and encrypted data cannot be lost. 3) The along with the migration of its associated VM. 2) After vTPM unique features [22]: 1) A virtual TPM instance can migrate the same functions of the physical TPM, and it also has some virtual TPM (vTPM) so that its capabilities can be used the resources of the same host machine. It is necessary to ensure a cloud service platform is safe and trusted.

In conclusion, one challenge of C-RAN is virtualization adoption to ultimately realize dynamic cloud-level resource allocation and management [32]. Current study does not concern how to support multiple operators and allow them to collaborate with each other in a trustworthy way in order to save each one’s cost [6]. An ideal C-RAN platform should have a trusted cooperation mechanism to support multiple operators and allow them to collaborate with each other in the VBS pool. From the view of typical security requirements of the C-RAN service plane, designing a trusted authentication and trustworthy cooperation mechanism is a very effective way to overcome the above threats or attacks. But the literature still lacks studies on this issue.

B. TRUSTED COMPUTING AND INTEGRITY MEASUREMENT

In the C-RAN architecture, multiple VBS pools share a hardware platform which leads to reduced operating expenses and improves hardware utilization through virtualization. However, it has brought about a slew of concerns with regard to security. The applications of the VBS pool technology thus give rise to stringent security requirements in the areas of platform integrity, trusted authentication and trustworthy cooperation. Trusted Computing (TC) is a good solution to satisfy these security requirements based on the integration of hardware platform and trust root, which has gained great ground in industry and academia [18]. In 2007, the Trusted Computing Group (TCG) [19] proposed a series of technical specifications and core components, which includes the Trusted Platform Module (TPM) [12], [20], [22] and the TCG Software Stack (TSS) [21]. The virtualization technology makes it possible that multiple virtual machines (VM) share the resources of the same host machine. It is necessary to virtualize TPM (vTPM) so that its capabilities can be used for all VM running on the platform due to the limitations of the physical TPM. vTPM is designed to implement the same functions of the physical TPM, and it also has some unique features [22]: 1) A virtual TPM instance can migrate along with the migration of its associated VM; 2) After vTPM migrating, its keys and encrypted data cannot be lost; 3) the vTPMs are isolated to each other among different VMs, but they can interact with each other in a same host machine. Intel® SGX [38] protects selected code and data from disclosure or modification through the use of protected areas of execution in memory. These approaches and protocols can ensure a trustworthy cloud platform and provide security related services (e.g., integrity measurements of a system, remote attestation and sealing or binding, as well as secure execution). However, its usage or adoption in C-RAN is still lacking. They cannot ensure that the trust relationship between two parties can be sustained as expectation after attestation based on a sustaining policy.

In [23], Krautheim proposed a new private virtual infrastructure (PVI) scheme, which is a cloud resource management and security model. TPM is used as a basis for trust in the PVI. Through TPC technology, PVI gives rights to users based on their security level and restrict cloud resources that the user is allowed to access, which reduces the risk of a cloud platform provider by sharing the security responsibility between the cloud provider and the customers.

Sadeghi and Stüble [24], Sadeghi [25] first analyzed some drawbacks of remote trusted attestation based on computer hardware platforms and software configuration, which is not beneficial for backup and update of this platform [24]. They also discussed two shortcomings of existing solutions for virtual TPM. First, after one platform’s VM and vTPM migrate to another platform with different integrity measurement, the VM can no longer access the keys of vTPM and the data protected by those keys. Not only that, but the original key generation strategies or other security properties are also missing. Second, when the software of one platform performs an update, the same problems happen. Then, they designed a novel property-based attestation vTPM architecture to solve the above problems through property-based attestation and sealing [25].

Nagarajan and Varadharajan [26] pointed out that the property-based trust attestation still has a problem: the whole attestation process introduces some uncertainties that reduce trust in the property-based attestation and cause such a problem that server customers (end-users or other demanders) cannot be completely sure whether the server truly satisfies the claimed properties. For server customers, these uncertainties mainly reflect in the following aspects: first, a dynamic system cannot go down in some scenarios, and it is highly stable and updated constantly with new functions. But, this dynamic system exists vulnerability that the measured value at boot time is not equal to the state of the system at the time of attestation. The server customers may not trust this value as time goes by. Second, in property-based attestation, the various properties of the platform need the corresponding binary measurements and property certificates to prove their credibility. However, a third-party Certification Authority (CA) is responsible for issuing and managing these certificates. CA only issues the certificates for each stand-alone component and not for the whole system environment of the server provider, which causes an uncertainty on the
trust of all components coming together in one platform, and it is difficult to ensure that these components’ property certificates are effective under the influence of each other. Third, no matter how credible CA property certificate is, the trust value of this certificate will be reduced as long as the server customers do not recognize that CA is trustworthy. For solving the above uncertainties, Nagarajan et al. designed a Trust Enhanced Security Model (TESM), which had led to a further development of trusted computing. However, it also has a problem that the authors did not consider: how to maintain the trust relationship between the both sides in next process. After a successful authentication, an unsafe scenario may occur that no matter how the certifier’s platform changes, the challenger will still consider it trustworthy. In our scheme, we overcome this problem in the above schemes and maintain the trust to support cooperation fulfillment by creating a trust policy after trust attestation and let TPM ensure the execution of the trust policy.

C. GAME THEORY

Game theory belongs to applied mathematics. It is a mathematical modeling method to help rational decision makers choose conflict or cooperation in order to find an optimal behavior strategy [1]. Game considers the individual’s predicted and actual behaviors in the game and studies their optimization strategies. In a game, every rational player wants to find an optimal solution to maximize their own utilities, which aims to increase benefits and reduce costs. There are some basic elements in a game, which mainly include player, strategy, payoff, outcome and equilibrium. In a game, each participant who has a right to make a decision becomes a player. Strategy is a player’s plan that is feasible throughout the game. If there are some strategies for a player to choose in a game, then the game is called a finite game, otherwise it is an infinite game. The result of each player at the end of a game is payoff. In a game, the strategy a player chosen affects not only its own payoff but also the other players’. And the combination of all payoffs is the outcome of this game. Equilibrium is the meaning of balance literally. It refers to the optimal strategy combination of all players. Nash Equilibrium (NE) refers to a stable state where every player has no motivation to change its current strategy. NE is a game solution concept that can help forecast a player’s action when given the other players’ actions [34].

Generally, the games can be divided into cooperative game and non-cooperative game. The non-cooperative game cannot be realized by stimulation and restraint. From the time series of players’ actions, the games are further divided into two categories: static game and dynamic game. In the static game, players choose their strategies at the same time or not, but the latter does not know what strategy the first player has taken. In the dynamic game, players have a sequence of actions, and the latter can observe the action selected by the first one. According to players’ understanding of others, the games are divided into game with complete information and game with incomplete information. In a game with complete information, each player has accurate information about the characteristics of other players, such as their strategy spaces, and payoff functions. The game with incomplete information refers to a game that at least one player has the inaccuracy of information about the characteristics, strategic spaces and payoff functions of other players.

Al-Dhanhani et al. [36], [37] applied a repeated non-cooperative game to analyze the free-riding behaviors inside collaborative groups in educational social applications. Each player in this game model can post a request and answer others’ requests based on Tit-for-Tat strategy. The simulation results show that the Tit-for-Tat strategy cannot eliminate free-riding behaviors effectively. The authors pointed out a possibility to suppress free-riding behaviors by introducing reputation [37] and punishment [36]. Shen et al. [35] applied a social dilemma game model to study whether network entities would like to accept a Global Trust Management system for unwanted traffic control. They proposed a trust-based punishment mechanism and an incentive mechanism to motive the adoption of the unwanted traffic control system. Gao et al. [33] also used a social dilemma model to analyze the acceptance of a cloud data access control system based on reputation. They added cloud service provider’s reputation to the game and built a repeated public-goods game to study whether users want to store their own data at the cloud based on a reputation mechanism. In Section IV we will analyze the acceptance of I LCS for fostering cooperation among various operators based on the game theory.

In this paper, we aim to develop an effective scheme that supports multiple operators to cooperate with each other in a distributed environment. Through this scheme, multiple operators’ VBS pools can collaborate in a secure and trustworthy way. We focus on trust maintenance based on initial trust attestation, which was not considered in the previous work of other researchers.

III. INTER-OPERATOR COOPERATION SCHEME

In this section, we detail the system structure, the protocol of trust attestation and cooperation, the procedure of network resource leasing, rental provision, rental selection and rental accounting in IOCS.

The IOCS aims to support multiple operators based on the C-RAN architecture and allows them to collaborate with each other in a trustworthy way in order to save each one’s cost. It securely allows one operator’s subscribers to consume network resources of the others to gain expected quality of 5G services when its own network resources cannot satisfy the QoS requirements.

We set up an access trust management pool that contains a number of VBS trust managers, each of which takes care of one operator’s VBS pool (i.e., radio resources). In this pool, tokens are issued among VBS trust managers to allow radio resource rental and utilization in a general and secure way and balance network resource usage across multiple operators’ VBS pools. Concretely, the trust manager of one operator applies trust attestation to ensure that the VBS pool...
and the VBS trust manager in another operator is trustworthy as expectation and embed its cooperation policy into it for secure cooperation. When an operator’s network resource is not sufficient, its VBS trust manager contacts other VBS trust managers by providing a rental request. The other VBS trust managers offer rental to the requester based on their provision policies by considering such factors as current status of resource consumption (free resources), rental request, priority of resource rental, agreement with the requester, estimated resource demand in a requested period, etc. The requesting trust manager compares the offers from other TMs and decides the rental based on its decision strategy, e.g., credit venture evaluation of the rental providers and their reputation. Then, the access trust management pool locates the selected operator (TM and VBS pool) to handle the networking of another operator’s subscribers.

The lending operator’s VBS trust manager counts the rental time and consumed resources and reports to the renting one in a trustworthy way, supported by the lender’s trust attestation, trust monitoring and trust assurance in accordance with the renting policy. A token is generated that contains the rental time, the consumed resources and the unit charge. It is signed by both the renting operator and the lending operator. This token can be applied to claim rental profits.

A. NOTATIONS

For easy reference, Table 1 summarizes the notations used in this section.

<table>
<thead>
<tr>
<th>Notation</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>TM&lt;sub&gt;m&lt;/sub&gt;</td>
<td>The trust manager m</td>
</tr>
<tr>
<td>O&lt;sub&gt;i&lt;/sub&gt;</td>
<td>The operator i</td>
</tr>
<tr>
<td>fr&lt;sub&gt;i&lt;/sub&gt;</td>
<td>The free resources of operator i</td>
</tr>
<tr>
<td>rr&lt;sub&gt;_i&lt;/sub&gt;</td>
<td>The requested resources to operator i</td>
</tr>
<tr>
<td>Sgn&lt;sub&gt;(x, y)&lt;/sub&gt;</td>
<td>The signature of user y on x</td>
</tr>
<tr>
<td>cr&lt;sub&gt;i&lt;/sub&gt;</td>
<td>The consumed resources</td>
</tr>
<tr>
<td>α, β, γ, δ</td>
<td>The weighting parameters</td>
</tr>
<tr>
<td>R&lt;sub&gt;A&lt;/sub&gt;</td>
<td>The total rental account</td>
</tr>
<tr>
<td>RR&lt;sub&gt;_m&lt;/sub&gt;</td>
<td>The rental request of TM&lt;sub&gt;_m&lt;/sub&gt;</td>
</tr>
<tr>
<td>RO&lt;sub&gt;_m&lt;/sub&gt;</td>
<td>The rental offer of TM&lt;sub&gt;_m&lt;/sub&gt;</td>
</tr>
<tr>
<td>τ&lt;sub&gt;_m&lt;/sub&gt;</td>
<td>The rental time of TM&lt;sub&gt;_m&lt;/sub&gt;</td>
</tr>
<tr>
<td>SK&lt;sub&gt;_m&lt;/sub&gt;</td>
<td>The private key of TM&lt;sub&gt;_m&lt;/sub&gt;</td>
</tr>
<tr>
<td>rp&lt;sub&gt;i,j&lt;/sub&gt;</td>
<td>The priority of resource rental TM&lt;sub&gt;_i&lt;/sub&gt; to TM&lt;sub&gt;_j&lt;/sub&gt;</td>
</tr>
<tr>
<td>er&lt;sub&gt;i&lt;/sub&gt;</td>
<td>The estimated resource demand of TM&lt;sub&gt;i&lt;/sub&gt;</td>
</tr>
<tr>
<td>P&lt;sub&gt;i,j&lt;/sub&gt;</td>
<td>The policy of TM&lt;sub&gt;i&lt;/sub&gt; on TM&lt;sub&gt;j&lt;/sub&gt;</td>
</tr>
<tr>
<td>up&lt;sub&gt;i,j&lt;/sub&gt;</td>
<td>The unit rental price of TM&lt;sub&gt;i&lt;/sub&gt; to TM&lt;sub&gt;j&lt;/sub&gt;</td>
</tr>
<tr>
<td>TV&lt;sub&gt;i,j&lt;/sub&gt;</td>
<td>The trust value of TM&lt;sub&gt;i&lt;/sub&gt; on TM&lt;sub&gt;j&lt;/sub&gt;</td>
</tr>
<tr>
<td>T&lt;sub&gt;i,j&lt;/sub&gt;</td>
<td>The personal trust value of TM&lt;sub&gt;i&lt;/sub&gt; according to past experiences on TM&lt;sub&gt;j&lt;/sub&gt;</td>
</tr>
<tr>
<td>T&lt;sub&gt;rec&lt;/sub&gt;</td>
<td>The trust recommendation of TM&lt;sub&gt;_m&lt;/sub&gt; on TM&lt;sub&gt;_j&lt;/sub&gt;</td>
</tr>
<tr>
<td>S&lt;sub&gt;_i&lt;/sub&gt;</td>
<td>The selection index of TM&lt;sub&gt;_i&lt;/sub&gt; on TM&lt;sub&gt;_j&lt;/sub&gt;</td>
</tr>
<tr>
<td>Cert&lt;sub&gt;X&lt;/sub&gt;</td>
<td>The execution environment certificate of X</td>
</tr>
<tr>
<td>Pool&lt;sub&gt;n&lt;/sub&gt;</td>
<td>The virtual base station pool n</td>
</tr>
</tbody>
</table>

B. SYSTEM STRUCTURE

The system structure is shown in Fig. 1. There are a number of different operators: O<sub>1</sub>, O<sub>2</sub>, ..., O<sub>n</sub>, each of which has its RHHs. Operator O<sub>i</sub> owns its VBS pool (Pool<sub>i</sub>). VBS trust manager TM<sub>i</sub> manages Pool<sub>i</sub> and cooperates with other operators’ VBS trust managers. VBS Pools communicate and cooperate with each other through their trust managers. VBS pools connect with core network functional units.

C. TRUST ATTESTATION AND COOPERATION

In order to ensure trust cooperation among multiple VBS pools, we propose a protocol of trust attestation and cooperation, as shown in Fig. 2. Before O<sub>i</sub> collaborates with O<sub>j</sub>, it needs to establish a trust relationship with O<sub>j</sub>. It should also verify VBS Pool<sub>2</sub> and TM<sub>2</sub> in case of any intrusions and attacks happened. After mutual authentication, trust-maintenance mechanism is set up between the two parties. If both VBS pool and TM apply the TPM with a root trusted module (RTM), the trust maintenance is controlled through the conditions defined by the RTM [11]. The RTM (implemented by TPM) is applied for verifying some intended
purposes of a client and ensuring that the VBS pool will work as its TM’s expectation and a TM will work as another TM’s expectation, and vice versa. Note in [11] and [32] to achieve trust attestation and ensure that we can apply the trust-maintenance mechanism as described in [11] and [32]:

1) TM\(_1\) generates its trust policy \(P_{1,2}\) with \(O_2\). TM\(_1\) challenges the execution environment of TM\(_2\). TM\(_2\) replies its execution environment certificate \(Cert\_TM\_2\) and its VBS Pool’s address.

2) TM\(_1\) verifies \(Cert\_TM\_2\). If the verification is positive, it challenges VBS Pool\(_2\)’s execution environment by getting VBS Pool\(_2\)’s execution environment certificate \(Cert\_Pool\_2\).

3) By getting positive verification on \(Cert\_Pool\_2\), TM\(_1\) sends \(P_{1,2}\) to TM\(_2\). TM\(_2\) embeds \(P_{1,2}\) into its execution platform, which monitors TM\(_2\)’s execution environment and checks any changes that violate \(P_{1,2}\) at TM\(_2\). TM\(_2\) further passes \(P_{1,2}\) to VBS Pool\(_2\), which then embeds \(P_{1,2}\) into VBS Pool\(_2\)’s platform. TM\(_2\) monitors whether the VBS Pool\(_2\)’s execution environment satisfies \(P_{1,2}\) by checking any changes at VBS Pool\(_2\).

4) If \(P_{1,2}\) is violated at either VBS Pool\(_2\) or TM\(_2\), TM\(_2\) will inform TM\(_1\) to perform corresponding actions, e.g., stop cooperation with TM\(_2\) and deny rental account in TM\(_2\).

If TM and VBS pool apply TCP with a RTM, we can apply the trust-maintenance mechanism as described in [11] and [32]:

1. When a TM’s resources are not sufficient, it requests rental from other operators. The procedure about TM\(_1\) to rent resources from TM\(_2\) is shown in Fig. 3.

2. TM\(_1\) broadcasts \(RR_1\) to the other TMs. When the other TMs receive \(RR_1\), they check their free resources and provide rental offer \(RP_1\) (refer to Section III-E for details).

3. TM\(_1\) compares all rental offers and selects the best one based on its selection strategy (more details can be found in Section III-E).

4. Suppose that TM\(_2\) is selected, TM\(_1\) requests locating networking access to the selected VBS pool Pool\(_2\) with message \(Sign(RO_2, SK_1)\), where \(SK_1\) is the private key of TM\(_1\).

5. TM\(_2\) replies \(Sign(Sign(RO_2, SK_1), SK_2)\) for confirming the selection.

6. TM\(_1\) locates networking access to TM\(_2\), which processes the request of TM\(_1\) according to its VBS pool Pool\(_2\). Meanwhile, TM\(_2\) counts the consumed resources RA during the whole rental period.

7. After the rental time \(t_{r1}\) is over, TM\(_2\) sends the rental account package \(Sign(RA, SK_2)\), where RA is the rental account (refer to Section III-E for a method of RA calculation).

8. TM\(_1\) checks and confirms the account package if it believes that the previous attested trusted platform of TM\(_2\) and VBS Pool\(_2\) are not intruded and then sends its acknowledgement \(Sign(Sign(RA, SK_2), SK_1)\) to TM\(_2\).

E. RENTAL PROVISION, SELECTION AND ACCOUNTING

When TM\(_j\) gets a rental request from TM\(_i\), it generates its rental offer by considering the following factors:

- current status of resource consumption, i.e., free resources \((fr_j)\); (Herein, we hold such a policy that each operator should satisfy its own users first before lending any extra resources to other operator.)
- requested resource \((rr_j)\);
- priority of resource rental to the requesting TM\(_i\) \((rp_{i,j})\);
- agreement between TM\(_i\) and TM\(_j\);
- estimated local resource demand \((er_j)\) in the demanded future period \(e_{t_j}\).

Algorithm 1 specifies how to calculate the rental offer. Our algorithm aims to ensure the offered rental can satisfy the requesting party’s QoS expectation.

Algorithm 1 Rental Offer Calculation

If there is no request from a TM \((TM_i)\) with higher priority, that is, there is no requesting \(TM_k\) with \(rp_{k,i} > rp_{i,j}\):

If \(fr_j < rr_j\), reject request; Else

If \(er_j + rr_j < fr_j\)

Generate rental offer package \(RO_i\) based on agreed price \(up_{i,j}\) between two involved operators.

Else

Process the next TM request.

D. COOPERATION PROCEDURE

When an operator’s resources are not sufficient, it requests rental from other operators. The procedure about TM\(_1\) to rent resources from TM\(_2\) is shown in Fig. 3.

1) TM\(_1\) generates a rental request \(RR_1\), which contains the volume of requested resources \((rr_1)\) and rental time \((t_{r1})\):
Trust value \((TV_{i,j})\) of \(TM_i\) on \(TM_j\) is generated based on \(TM_i\)’s personal trust according to past experiences \((T_{i,j})\) and other \(TM\)’s recommendation \((T_{n,j})\) as shown in the following equation:

\[
TV_{i,j} = \alpha \times T_{i,j} + \beta \times \frac{\sum_{n=1}^{N} (1 - |T_{i,j} - T_{n,j}|)}{N - 1} \times T_{n,j},
\]

where \(\alpha\) and \(\beta\) are weighting parameters to balance the contribution of \(T_{i,j}\) and \(T_{n,j}\) in trust value generation. Herein, the use deviation \(|T_{i,j} - T_{n,j}|\) to tailor the contribution of \(T_{n,j}\) in \(TV_{i,j}\) calculation in order to resist bad mouthing attacks.

An example decision function is shown in (1).

\[
S_{i,j} = \gamma \times TV_{i,j} + \delta \times \frac{1}{up_i,j}, \quad (1)
\]

Obviously, the decision is made by considering trust value \(TV_{i,j}\) and unit rental price \(up_i,j\). Parameters \(\gamma\) and \(\delta\) are weighting factors to weight \(TV_{i,j}\) and \(up_i,j\).

The requesting trust manager \(TM_i\) selects \(TM_j\) with the biggest \(S_{i,j}\). Then the access trust management pool locates the selected operator to handle the networking access of another operator’s subscribers.

2) RENTAL ACCOUNTING
The rental time \((rt_{i,j})\) and consumed resources \((cr_{i,j})\) are counted by the lending operator’s VBS trust manager and reported to the renting one in a trustworthy way. A token is generated that contains the rental time, consumed resources and unit charge. It is signed by both the renting operator and the lending operator. This token can be used for claiming rental profit. Concretely,

\[
RA_{i,j} = rt_{i,j} \times cr_{i,j} \times up_i,j.
\]

The token is \(Sign(Sign(RA, SK_2), SK_1)\).

IV. SECURITY ANALYSIS AND PERFORMANCE EVALUATION
In this section, we analyze the security of the proposed scheme and evaluate the performance of IOCS based on scheme implementation in terms of trust attestation accuracy, operation efficiency, and reasonable resource consumption (including operation time, memory cost, CPU consumption, and communication cost). Furthermore, we apply game theory to analyze the possibility of potential cooperation among multiple operators.

A. SCHEME IMPLEMENTATION
We implemented IOCS in Lenovo ThinkServer TS250 with Intel Xeon E3-1225 v5 CPU of 3.30GHz, 2TB hard disk and 32GB RAM. We deployed a cloud computing management platform to simulate the access trust management pool that managed different operators’ VBS pools and TMs based on OpenStack. The OpenStack is an open source cloud computing resource-management tool. It can quickly deploy a virtual environment and create multiple virtual servers in this environment \([27], [28]\). Besides, any users can deploy their own applications in these servers. We built up eleven 64-bit RedHat Enterprise Linux Servers (simulated eleven operator nodes) in OpenStack to simulate the process of remote trust attestation and cooperation among different VBS pools and TMs. A MySQL database is installed in each server, which is applied to simulate the network resources of each operator. Then, we used TPM emulator (one vTPM instance developed by Mario Strasser in 2004 \([29], [30]\)) to simulate the RTM and store the AIK in each server. The emulator can implement the functions of vTPM, such as platform identity authentication, platform attestation and certification. Based on the above, we implemented the IOCS with C/C++ language and demonstrated our scheme’s functions by calling the API provided by the TSS. In the TPM emulator, TrouSers is used to provide the same functions and APIs of TSS, and TCG Device Driver Library (TDDL) is used to facilitate interaction between TSS and TPM device drivers. We employed the TPM emulator daemon (TPMD) that is a user space daemon to implement the functions of TPM, such as a daemon application, a TPM emulator engine and cryptographic functions \([10]\).

Based on our implementation, we comprehensively verified and tested the features of our IOCS. Through the TPM emulator, each virtual machine can provide its own PCR lists, system event logs and credentials to complete trust attestation. Once trust authentication is successful, cross-network cooperation among multiple mobile operators’ VBS pools will be established based on a relevant trust policy. We designed a heartbeat mechanism, which is a data packet that can detect the validity of nodes, to ensure reliable communications between the tenant and renter. If any party violates the trust policy, the TPM can warn the other party through the heartbeat mechanism. For example, when the virtual machine configuration (e.g. router network or firewall configuration) changes, the PCR will change accordingly and then the warning will be sent if this change is against the trust maintenance or sustainment policy.

B. SECURITY ANALYSIS
In Section II, we discussed the security issues and requirements of the C-RAN service plane. The motivation of our work is to design a comprehensive and universal solution for trusted cooperation across multiple cellular networks in C-RAN. Our scheme has the following security features.

First, the IOCS provides security in three levels. The OpenStack platform can issue tokens to verify the identity of the VBS Pool. The RTM module not only ensures the security of virtual machine, but also realizes remote authentication. We dynamically maintain the trust relationship between the requester and the resource provider based on the procedure of trust cooperation according to the policy for trust relationship maintenance.

Second, the trust attestation we adopt has an improved integrity measurement. It can measure specified related configuration files or log files based on our proposed trust attestation protocol and trust cooperation procedure, as well
as the trust maintenance or sustainment policy. During the cooperation of two operators, the RTM of one party warns another party through the heartbeat mechanism whenever the platform’s configuration status and key files changes are detected.

Finally, the selection strategy based on the trust value of each node effectively prevents threats from malicious nodes. For example, when the tenant gets multiple rental offers, it can select the most reliable one based on its trust in the renter.

C. PERFORMANCE TEST AND EVALUATION

1) CORRECTNESS TEST

We first tested execution correctness of our scheme implementation in the experimental environment by verifying whether each module is connected and integrated successfully.

a: TPM and TDDL Integration Test

After successfully installing and deploying the TPM emulator, we started to test this module’s deployment and running state. The start-up process of the TPM includes the detection of a random number generator, the detection of the cryptographic algorithm engine, the detection of a key system, platform self-test, plain text verification, etc. When the TPM is officially launched, it begins to wait for the TrouSers to connect to it via the API of the TDDL. The TPM emulator start-up process is shown in Fig. 4.

![FIGURE 4. TPM emulator successfully starts.](image)

After following the previous steps and completing the installation and deployment of the modules, we applied our test program to test the TDDL. When the TPM emulator and TDDL are integrated successfully, we can get TDDL driver status, TDDL device status, TDDL version and other information from the TDDL test program, as shown in Fig. 5.

![FIGURE 5. TPM and TDDL successfully integrate.](image)

b: TPM and TSS Integration Test

When the above integration was successful, we started to test whether the connection between TPM and TSS is successful. TSS needs to detect the running status of the TPM. In other words, after the TPM successfully runs, the TSS can be initiated and run. As shown in Fig. 6, the successful operation of Trusted Computing Group Service Daemon (TCSD) shows the success of TSS and TPM integration. When the above steps are completed, we can get the PCR value of the platform by running the “tpm_readpcr” command, as shown in Fig. 7.

![FIGURE 6. TSS successfully starts.](image)

![FIGURE 7. PCR value of the platform integrity metric.](image)

2) TRUST ATTESTATION TEST

a: AIK Certificate Application and Issue Test

A certificate application platform is running on a 64-bit RedHat Server virtual machine platform with a trusted computing environment. First, the virtual machine platform needs to apply for an AIK certificate from the trusted third party (TTP server), and then the platform information of the applicant, such as EK and public key, is verified by the TTP. The process is shown in Fig. 8, which mainly applies the asymmetric data block (asymBlob), the hashes of session key and the requester’s AIK public key for issuing AIK certificate. After passing the verification, TTP issues the AIK. Once receiving the AIK, the certificate application platform activates it via the Tspi_TPM_ActivateIdentity() interface as presented in Fig. 9.

![FIGURE 8. AIK Certificate Application and Issue Test](image)

b: Trust Attestation Process

First, the tenant sends a request connection to the renters, then the renters authenticate it. The verification mainly includes of identity information, metrics and PCR values, and the

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random number sent by the tenant. When this process is over, the trust between the tenant and the renters will be initiated. Next, the verifier sends the trust policy (the demands of trust maintenance) to the tenant, and vice versa. Both parties embed the trust policy into their TPM's execution environment by encoding it. The trust policy limits the tenant's execution environment by checking any changes that disobey the policy at the VBS pool of the tenant. The result is shown in Fig. 10 and Fig. 11.

The trust policy is a new kind of control specification. After the trust relationship is established, we further tested the effect of the trust policy when the platform configuration changes. The trust policy limits the tenant's execution environment by checking any changes that disobey the policy at the VBS pool of the tenant. The result is shown in Fig. 10 and Fig. 11.

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shown in Table 2, which mainly includes the process of AIK certificate application and issue, the process of trust verification (i.e., the process of trust credential transmission, the process of trust credential verification, and the process of platform integrity check), the process of policy transmission, and the process of entire trust relationship establishment. Here, we assume that the system has no malicious and malfunctioning nodes. When the number of nodes is gradually increasing, the operation time for the entire trust relationship establishment among different nodes is concluded in Table 3.

We further compared IOCS with one scheme about cloud service attestation [10] and another scheme [31] regarding operation time in terms of some similar procedures. The results are shown in Fig. 14, where the four abbreviations at abscissa axis refer to trust credential transmission, trust credential verification, platform integrity metrics, and trust verification, respectively. We can see that IOCS is the most efficient one.

### TABLE 3. Trust relationship establishment time with different number of operator nodes.

<table>
<thead>
<tr>
<th>Number of nodes</th>
<th>Time cost of successful attestation (in ms)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1111.36</td>
</tr>
<tr>
<td>2</td>
<td>1378.45</td>
</tr>
<tr>
<td>3</td>
<td>1567.34</td>
</tr>
<tr>
<td>4</td>
<td>1756.23</td>
</tr>
<tr>
<td>5</td>
<td>1945.12</td>
</tr>
<tr>
<td>6</td>
<td>2134.01</td>
</tr>
<tr>
<td>7</td>
<td>2322.90</td>
</tr>
<tr>
<td>8</td>
<td>2511.79</td>
</tr>
<tr>
<td>9</td>
<td>2700.68</td>
</tr>
<tr>
<td>10</td>
<td>2889.57</td>
</tr>
</tbody>
</table>

### FIGURE 14. Operation time of different solutions’ main process.

---

### b: Memory Cost and CPU Usage

In our scheme implementation, we applied many open source software, such as OpenStack, MySQL, TPM emulator and so on. These modules take up a certain amount of computing and storage resources. Therefore, we need to calculate the resource consumption in IOCS (i.e., memory cost and CPU usage). Assuming that there are two virtual nodes collaborate with each other credibly. We applied the average CPU (CPU avg) to represent CPU usages, which is the average percentage of CPU spent in 60 seconds. For the OpenStack and MySQL, we denote the memory cost as the dedicated memory (DP), which are about 123676-KB and 154712-KB, respectively. The DP refers to actual physical memory footprint in RAM. For the TPM emulator, TSS, remote procedure call (RPC) and daemon in the virtual machine, we also used the virtual memory size (VMS). The VMS includes the process and its shared library memory footprint in the virtual machine. It is the address space of the process and its shared library, and it does not reside in RAM. Due to its shared nature, the VMS of TSS is a bit large, which is 100214-KB. For others, the TPMD occupies 7056-KB and RPC costs 47586-KB. The daemon’s DP is 1500-KB. Considering the general configuration of a business server nowadays, the resource costs of the IOCS is acceptable. In addition, we compared the CPU utilization with and without the application of IOCS. As drawn in Fig. 15, we found that applying the IOCS costs about 7% more CPU overhead.
compared with the CPU highest occupancy. For CPU average, the IOCS occupies 25% of the CPU.

\[c\]: Communication Cost

In the trust attestation process, the size of the random number is about 40-bit. The AIK is an RSA signature key with a default size of 2048-bit. The process of trust credential transmission mainly includes the integrity metrics list and some PCR. The transmitted information is in the form of hash values, which is about 521-byte. In the trust cooperation process, the size of the heartbeat package in the heartbeat mechanism is about 5-byte. The total size of the trust policy is about 2-KB. Therefore, the total communication cost of the process of trust relationship establishment is about 3-KB in our scheme. For 5G networks, this communication cost is very small.

| TABLE 4. Notation about game theoretical analysis. |
|------------------------------|------------------|
| Notations | Description |
| \(u_i^f(t)\) | The utility of tenant \(i\) at time \(t\) |
| \(u_j^f(t)\) | The utility of renter \(j\) at time \(t\) |
| \(u_g(t)\) | The unit resource usage payment by subscribers at time \(t\) in the system (assume that the subscribers of \(i\) and \(j\) pay the same unit fee of resources) |
| \(u_f(t)\) | The basic maintenance and operation cost of unit resource in a normal situation at time \(t\) |
| \(r_f(t)\) | The basic unit rental fee paid by tenant at time \(t\) |
| \(I\) | The total amount of resources of tenant \(i\) |
| \(J\) | The total amount of resources of renter \(j\) |
| \(I'\) | The rented amount of resources of tenant \(i\) |
| \(J'\) | The lent amount of resources of render \(j\) |
| \(TV_j(t)\) | The trust value of renter \(j\), \(TV_j(t) \in [0, 1]\) |
| \(TV_i(t)\) | The trust value of tenant \(i\), \(TV_i(t) \in [0, 1]\) |
| \(l_{0_i(t)}\) | The total loss of tenant \(i\) at time \(t\) |
| \(A_{x,y}\) | The strategy space of tenant and renter |

4) ANALYSIS ON IOCS ACCEPTANCE BASED ON GAME THEORY

We modeled a static game model to analyze IOCS’s acceptance in practice. The tenant (i.e. tenant operator) and the renter (i.e. renter operator) are the players in this game. The players know each other’s information. We mainly analyze whether all players (i.e., operators) would collaborate with each other given their limited network resources and their status. For easy presentation, Table 4 summarizes the notations applied in our analysis.

Our model holds a number of assumptions for game theoretical analysis to investigate the acceptance of tenant operators and renter operators in the IOCS and its deployment condition.

Assumption 1: We assume there are only two types of players for simplification, both of which should treat their own subscribers with high priority. These two types of players are the renter with extra network resources, and the tenant without sufficient network resources. Each operator should firstly serve its own subscribers, if extra resources can be located, it can offer rental services to other operators.

Assumption 2: All players are rational in the game. They all take a personal optimal strategy to maximize their utilities. The renter’s strategy space is \(\{A_{r,1}, A_{r,2}\}\), where \(A_{r,1}\) means the renter cooperates with the tenant and \(A_{r,2}\) means the renter refuses to cooperate with the tenant. The tenant’s strategy space is \(\{A_{t,1}, A_{t,2}\}\), where \(A_{t,1}\) stands for the tenant cooperates with the renter and \(A_{t,2}\) stands for the tenant refuses to cooperate with the renter.

Assumption 3: Renters cannot be fully trusted. For a renter, dishonest behaviors in this collaborative process can affect its own trust value. For a renter with low reputation, its tenant has a high possibility to suffer loss.

Assumption 4: In this model, both the tenant \(i\) and the renter \(j\) want to make a profit from the rental.

Assumption 5: We assume that the subscribers of any operator pay the same unit resource usage fee.

Assumption 6: The tenant selects the renter that can provide it with sufficient resources it requested.

In our analysis, we consider the impact of the trust value on operator cooperation. We assume that there is a certain security risk to use the shared resources of network provided by a renter, which may cause some loss to tenant in this cooperation (i.e., \(l_{0_i(t)}\)). The trust value of the renter represents the security degree of network resources provided by it. In other words, the higher the trust value of the renter, the smaller the tenant’s loss. However, the higher the trust value of the renter, the more expensive its maintenance and operation costs. The renter need to pay more maintenance fee to obtain a higher trust value.

\(J\) denotes the total amount of resources of renter \(j\), among which there are \(J'\) redundant resources that can be rented. \(u_g(t)\) is the unit resource usage payment by subscribers at time \(t\). \(u_f(t)\) stands for the basic unit operation and maintenance cost of renter \(j\) at time \(t\) in a normal situation (e.g., without security and trust enhancement technologies applied). \(TV_j(t)\) is the trust value of renter \(j\), which requires renter \(j\) to spend more maintenance fee to maintain a higher trust value. If renter \(j\) does not rent its redundant resources, its utility at time \(t\) can be described as (3):

\[u_j^f(t) = u_g(t) \times (J - J') - u_f(t) \times J \times (1 + TV_j(t)). \tag{3}\]

Imagine tenant \(i\) renting some resources \(I'\) from renter \(j\). Renter \(j\) obtains rental benefit \(r_f(t) \times I' \times (1 + TV_j(t))\) from tenant \(i\) at time \(t\), where \(r_f(t)\) is the basic unit resource rental fee and \(r_f(t) \times I' \times TV_j(t)\) stands for the extra benefit that
Table 5. Utility matrix with trust.

<table>
<thead>
<tr>
<th></th>
<th>$A_{1,1}$</th>
<th>$A_{1,2}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$u_i^I(t)$</td>
<td>$ug(t) \times (J - J') - uf_j(t) \times (1 + TV_j(t))$</td>
<td>$ug(t) \times (J - J') - uf_j(t) \times (1 + TV_j(t))$</td>
</tr>
<tr>
<td></td>
<td>$\times J + rf(t) \times l' \times (1 + TV_j(t))$</td>
<td>$\times J + rf(t) \times l' \times (1 + TV_j(t))$</td>
</tr>
<tr>
<td>$u_i^J(t)$</td>
<td>$ug(t) \times I - uf_i(t) \times I \times (1 + TV_i(t)) +$</td>
<td>$ug(t) \times I - uf_i(t) \times I \times (1 + TV_i(t)) +$</td>
</tr>
<tr>
<td></td>
<td>$(ug(t) - rf(t) \times (1 + TV_i(t))) \times I' - (1 - TV_j(t)) \times l(t))$</td>
<td>$(ug(t) - rf(t) \times (1 + TV_i(t))) \times I' - (1 - TV_j(t)) \times l(t))$</td>
</tr>
</tbody>
</table>

Given $\alpha$, the expected utility of tenant $i$ when it chooses cooperation ($\beta = 1$) and rejects cooperation ($\beta = 0$) are:

$$\prod I(\alpha, 1) = (ug(t) - uf_i(t) \times (1 + TV_i(t))) \times I + (ug(t) - rf(t) \times (1 + TV_j(t))) \times I' - (1 - TV_j(t)) \times l(t).$$

$$\prod I(\alpha, 0) = (ug(t) - uf_i(t) \times (1 + TV_i(t))) \times I.$$

Given $\beta$, the expected utilities of renter $j$ when it chooses cooperation ($\alpha = 1$) and rejects cooperation ($\alpha = 0$) are:

$$\prod J(1, \beta) = ug(t) \times (J - J') - uf_j(t) \times (1 + TV_j(t)) \times J + rf(t) \times I' \times (1 + TV_j(t)).$$

$$\prod J(0, \beta) = ug(t) \times (J - J') - uf_j(t) \times J \times (1 + TV_j(t)).$$

1) When $ug(t) \times I' - rf(t) \times (1 + TV_j(t)) \times I' - (1 - TV_i(t)) \times l(t) > 0$, the mixed strategy NE of the game is the same as the pure strategy NE. To be specific, NE is achieved when both the renter and the tenant choose to cooperate.

2) When $ug(t) \times I' - rf(t) \times (1 + TV_j(t)) \times I' - (1 - TV_i(t)) \times l(t) \leq 0$, we can get the following result: $\prod I(\alpha, 1) \leq \prod I(\alpha, 1)$. This means, it is better for tenant $i$ to reject cooperation. Since $rf(t) \times I' \times (1 + TV_j(t))$ is a positive value, we can get the following result: $\prod J(0, \beta) \leq \prod J(1, \beta)$. Therefore, it is beneficial for renter $d\beta$ to choose cooperation.

In general, the renter’s dominant strategy is cooperation, which means no matter what actions the tenant chooses, the renter can always obtain more profits by cooperation. On the other hand, the tenant chooses strategies with regard to the value of $ug(t) \times I' - rf(t) \times (1 + TV_j(t)) \times I' - (1 - TV_i(t)) \times l(t)$. Obviously, the cooperation condition of the renter and the tenant is $(lo_i(t) - rf(t) \times I') \times TV_j(t) + ug(t) \times I' - rf(t) \times I' - lo_i(t) > 0$. When $TV_j(t) = 0$, big loss will make the tenant have no profit. When $TV_j(t) = 1$, it is possible to set proper $rf(t)$ and $ug(t)$ to benefit both parties.

Based on the above analysis, we can conclude that one operator can offer rental services to other operators to obtain extra benefits if extra resources can be located. So normal operators have a willingness to rent their network resources. However, if the reputation of the renter is low and its network resources are not secure, the tenant’s potential loss could be more than that the tenant can endure or more than the benefits that the tenant can obtain, then the tenant would not choose the renter to cooperate. In this situation, the tenant may prefer to choose a renter that can make it have low loss and high
utility. Therefore, the tenant will choose those renters that have a high trust value to reduce its potential losses. The less the loss that a tenant expects in the cooperation process with the renter, the higher the trust of the renter should provide. The only downside is that the tenant’s utility will be less than before since it need to pay more rental fee (refer to (6)). For the renter, if it wants to attract more tenants and get more benefits, the simple approach is to increase the security of its own network resources to gain high trust, which of course will cost the renter more.

V. CONCLUSION AND FUTURE WORK

In this paper, we proposed the IOCS to support multiple operators to share resources in a trustworthy and secure way based on the TCP technology in the infrastructure of C-RAN. Trust cooperation across multiple cellular networks is flexibly supported. It achieves trust attestation and cooperation among different VBS pools by applying RTM to monitor VBS pool configuration and ensure their changes compatible with trust policy. IOCS meets the demands of the 5G. It effectively reduces the TCO and roaming price by sharing and balancing the entire resources in the network. Performance evaluation and simulation results show that the IOCS has high operation efficiency and trust attestation accuracy. The game theoretical analysis further provides the utilities of renter operators and tenant operators, as well as their cooperation condition in the IOCS with their trust being considered.

Regarding the future work, we plan to further optimize our scheme in the following ways. We are ready to propose more effective and safe rental strategies in order to help inter-operator cooperation. For example, through blockchain technology, the traceability and non-repudiation of transactions among different operators can be guaranteed. Meanwhile, trustworthy trust evaluation can be further provided with high quality and granularity.

REFERENCES


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