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Quantum Cryptography for Wireless Network Communications

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Abstract — **It is well known that wireless networks have become one of the most important part used communication systems, in particular for ubiquitous computing. However, providing secure communication for wireless networks has become one of the prime concerns. Quantum cryptography, namely Quantum Key Distribution (QKD), offers the promise of unconditional security. In this paper, we shall extend our previous research work to a new method of integrating quantum cryptography for key distribution in 802.11 wireless networks. Our contributions, based on our previous results [1], are as follows: (a) We shall show how QKD can be used in IEEE 802.11 wireless networks to securely distribute the keys. (b) We shall introduce a method that take the advantage of mutual authentication features offered by some EAP variants of 802.1X Port-Based Network Access Control. (c) Finally, we present a new code called Quantum Message Integrity Code (Q-MIC) which provides mutual authentication between the two communication parties and its implementation**

I. Introduction

It is obviously fact we face that wireless networks are becoming ubiquitous in homes, offices and enterprises with its ability to provide high-speed high-quality information exchange between portable devices**.** As the wireless communication has gone through rapid advancements during the last few decades, an increasing number of government agencies, businesses and home users are either using, or considering using, wireless technologies in their environments [24]. Therefore it is obvious that in the near future wireless technology will dominate the communication industry. While wireless networks and its applications are becoming popular every day, security issues associated with it have become a great concern. In this paper we are going to make a novel method to create an implementation of quantum cryptography for key distribution in 802.11 networks.

As wireless communications use the airwaves, they are intrinsically more vulnerable to interceptions and attacks than its wired counterparts. As the service become more popular, there are a great number of security risks associated with the current wireless protocols and encryption methods [6, 8]. Some of the common types of attacks against

wireless networks are; Denial of Service (DoS) attacks, Identity theft (MAC spoofing), Man-in-the-middle attacks, ARP poisoning, etc. DoS attacks are typically associated with 802.11 wireless communications [24].

Based on the laws of physics, quantum cryptography allows exchange of cryptographic key between two remote parties with unconditional security. The foundation of quantum cryptography lies in the Heisenberg uncertainty principle, which states that certain pairs of physical properties are related in such a way that measuring one property prevents the observer from simultaneously knowing the value of the other. So that act of an eavesdropper intercepting a photon will irretrievably change the information encoded on that photon, thereby detecting any security breach. It uses quantum states of photons to transfer cryptographic key material. Quantum cryptography is used to produce and distribute a key, known as Quantum Key Distribution (QKD). Several QKD protocols such as BB84 [7], B92 [20] and six-state [18] exist as of now. Out of those, BB84 is more popular and widely used in practical networks [25]. As the nature of BB84 and B92 [7, 18, 20, 21, 22] we have chosen a variation of BB84 called SARG04 (Scarani, Acin, Ribordy, and Gisin) [21] to employ in our current work. SARG04 is robust against photon-number splitting (PNS) attack [21, 22]. Explaining how SARG04 protocol works is not in scope of this paper. QKD has gone through significant advancements in optical networks [17, 19, 26, 27]. However, QKD with respect to free-space is showing rather slow progress. One of the main reasons for this slow progress in free space photon transmission is the difficulty in providing Line-Of-Sight (LOS) between the transmitter and the receiver for long distances. However, there are some papers discussed this issue [23, 28], we may use different models for different situations of the multi-path communication channels, such as almost-LOS (ALOS), quasi-LOS (QLOS), non-LOS (NLOS) with responding statistic distributions, which will not be discussed in our current paper.

In our work, we target the IEEE 802.11 wireless network to integrate with quantum cryptography.

Since the coverage area of 802.11 network small, the line-of-sight issue between the participating entities can be minimized. Also, for such a small distances, the impact to the photon transmission from environmental conditions such as noise is very low. Also we shall discuss this with statistic models in another paper to focus on ALOS and QLOS cases.

The IEEE 802.11 [2] wireless local area networks seem to present high interest to be used with quantum cryptography due to various reasons [7]. In fact, put the statistic models aside, one of the main advantages we can take is the range of coverage offered by IEEE 802.11 networks. The range of a typical WLAN node is about 100 m. So that 802.11 networks deployed in places like coffee shops, air ports, conference halls etc. This offers the line-of-sight path between the users and network apparatus.

On the other hand the applications that make use of 802.11 requires secured communication path with the service provider. Quantum cryptography has the potential to offer this much needed secured data communications for 802.11 wireless networks. Hence it is worth exploring the possibility of using Quantum Cryptography in 802.11 WLANS.

II. IEEE 802.11i Standard

Before we introduce our new protocol, we need to have a closer look at IEEE 802.11i standard as some of which we shall introduce into our current work. The security of 802.11 is defined by Wired Equivalent Privacy (WEP). However WEP was identified by cryptanalysts to have severe security weaknesses. As a result of this, an amendment to the IEEE 802.11 standard called IEEE 802.11i [3] was approved in 2004.

IEEE 802.11i is designed to provide enhanced security in the Medium Access Control (MAC) layer for 802.11 networks. It defines two classes of security algorithms: Robust Security Network Association (RSNA) and Transition Security Network (TSN). IEEE 802.11i describes two new confidentiality algorithms to address those two cipher suites, namely Temporal Key Integrity Protocol (TKIP) and Counter-mode/CBC-MAC Protocol (CCMP) respectively [12]. IEEE 802.1X offers an effective framework for authenticating, managing keys and controlling user traffic to protect large networks. It employs the Extensible Authentication Protocol (EAP) [13] to allow a wide variety of authentication mechanisms, which we are going to keep it in our current work.

It is noted that 802.1X authentication process happen among three main elements. The Authenticator or the Access Point allows only the supplicants who are authorized by the authentication server to gain access to the network.

RSNA defines two types of key hierarchies to divide initial key material into useful keys. The two key hierarchies are: Pairwise key hierarchy, which is used to protect unicast traffic and, Group key hierarchy which is used to protect multicast and broadcast traffic. We can show the Pairwise key hierarchy in Figure 1.
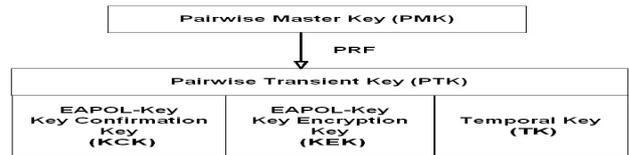

Figure 1: IEEE 802.11i Pairwise Key Hierarchy [3].

III. QKD for Wireless Networks

As described in above, wireless networks are subject to various security risks. Exchanging data over a wireless network must be done with great care because traffic interceptions in wireless networks are much easier. Therefore, in order to provide privacy for the users, it is essential to authenticate users with the network elements. Although there are lots of researches are happening to improve this daunting task of providing secure data communication to users, they are still subject to security attacks. Quantum cryptography or QKD is one area that did not get enough attention in wireless networks so far with respect to providing secrete key distribution. Even though there are lots of things need to be investigated before this technology applies to the real world. Our current work is part of the contributions toward to the final successful target. In this section we are going to build a bridge between QKD and wireless networks.

It is well known that the classical public-key cryptography uses asymmetric keys, with one that is private and another one that is public. The receiving station uses the matching private key to decrypt the data upon reception. Each station keeps their private key hidden in order to avoid compromising encrypted information. In addition, to protecting information from hackers, stations can use public key cryptography to authenticate themselves to other stations or access points. The intrinsic weakness of this classical public-key cryptography is based on the fact that the private key is always linked mathematically to the public key [14]. Due to this reason, it is always possible to attack a public-key system if the eavesdroppers equipped with sufficiently large computational resources. Therefore, the mathematical problem to derive the private key from public key must be as difficult as possible. Hence those systems cannot provide any indication of eavesdropping or guarantee the key security.

Quantum cryptography exploits the fundamental laws of quantum physics where nobody can measure a state of an arbitrary polarized photon carrying information without introducing disturbances.

Classical key distribution can always be passively monitored, without the legitimate users being aware that any eavesdropping has taken place. Whereas in quantum mechanics, any projective measurement will induce disturbances hence eavesdropping can be detected. Due to this reason, use of QKD in wireless key distribution will provide huge advantage with respect to data security.

In 802.11i networks there are two places where the mutual authentication can be employed. Firstly, by selecting a correct EAP type such as EAP-TLS, EAP-TTLS that offer mutual authentication during IEEE 802.1X authentication process. Secondly, the IEEE 802.11i 4-way handshake makes the mutual authentication happens in second and third messages. In the second message of 4-way handshake, authenticator receives the reply and message integrity code (MIC) from the supplicant. Authenticator checks the received and calculated MIC values to authenticate the Supplicant. In the third message, Authenticator sends the calculated MIC to the Supplicant. Supplicant then checks the MIC to authenticate the Authenticator, achieving mutual authentication.

IV. The Proposed Protocol

In our work, we paid special attention on the stage where the mutual authentication takes place in 802.11i networks. Therefore, we shall take the advantage of EAP types such as EAP-TLS, EAP-TTLS which offer mutual authentication, to merge 802.11i networks with QKD. In order to make QKD well match wireless communications, i.e. our aim is to introduce quantum key transmission soon after the 802.1X authentication is completed. The proposed protocol is shown in figure 2.

As described in flow 13 of figure 1, the last message of 802.1X protocol is the EAPOL message giving the EAP Key from Authenticator to the Supplicant. Since the two parties are mutually authenticated at this stage, we know that this message is genuine. We use this message as the starting point of quantum transmission. By this way we can safely start the quantum key exchange. As soon as the Supplicant receives the EAP Key message, the communication switches to quantum channel.
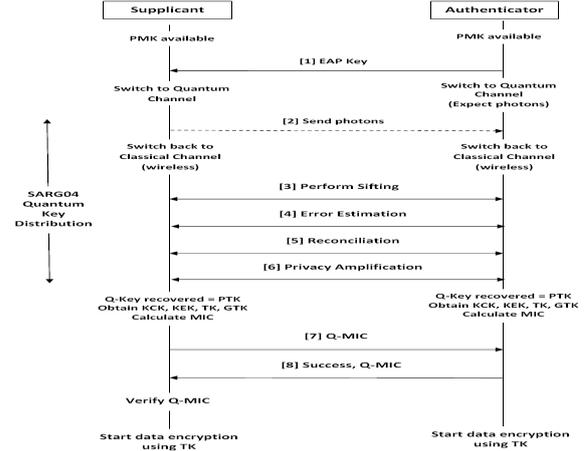

Figure 2: The Proposed Protocol

Once the photon transmission finishes, the communication switches back to classical wireless channel. Afterwards they complete the SARG04 quantum key exchange as shown in flows 3 to 6 of Figure 2. Due to atmospheric noise, dark counts in the photon detectors etc, lot of errors have been introduced into the transmission. Some of the transferred bits will get discarded during the final key recovery process of SARG04 protocol. Our next aim is to set the length of Q-Key equal to the length of PTK. For example, CCMP, PTK is 256 bits, while TKIP occupies 384 bits for PMK. So that we have to make sure the derived Q-Key will contain bits greater than or equal to the number of bits of PTK. We get this stripped Q-Key as the PTK.

Then from PTK, we can derive KEK, KCK and TK, while from KCK, MIC can be calculated. We shall use this MIC in our subsequent protocol messages to implement mutual authentication. In order to simplify the operation in wireless networks at this stage, Supplicant performs XOR operation with the MIC and the first set of bits of equal length in PMK. We call this resulted MIC as Quantum MIC (Q-MIC) and make the following protocol:

Q-MIC = (*MIC*) XOR (*first bits of PMK equivalent to the length of MIC*)

The Supplicant then sends the Q-MIC to Authenticator as shown in flow 7 of Figure 2. Upon receiving Q-MIC, Authenticator verifies the Q-MIC. Since the Authenticator is in possession of all the keys, it can calculate its own Q-MIC and compares with the one came from the Supplicant. If they match, the Supplicant is authenticated.

Supplicant verifies the Q-MIC to authenticate the Authenticator, thus achieving the mutual authentication. From now on, both parties use TK to encrypt the data and start secure communication and also use the GTK for multicast applications if needed.

Recent research work explores some of the flaws of 4-way handshake [5, 6, 8, 16]. It was shown that

the message 1 of 4-way handshake is subject to DoS attacks. For example, intruders can flood message 1 to the supplicant after the 4-way handshake has completed, causing the system to fail. Since key distribution of our protocol is done by the SARG04 protocol.

In order to under our protocol let's assume an eavesdropper send a fake photon transmission towards Authenticator soon after the EAP Key message (flow 2 of Figure 2). Then once the Q-Key is derived by SARG04 process, supplicant sends Q-MIC to Authenticator in flow 7. Authenticator can check this Q-MIC value as it has all the ingredients to generate its own Q-MIC. Therefore, any fake SARG04 processes can be known at this stage.

V. Implementation of QKD

The Quantum key transmission happens in two stages, in terns of concepts, which can be shown in Figure 3. It is noted that in Figure 3 the Wi-Fi connections are classical channels and the "optical Fiber" channels are quantum channels.

Stage1:Quantum channel (one way communication) This transmission could happen in either through free space or optical fiber. At present this implementation is being done at the Lab.

Stage 2:Classical channel (two way communication) This phase deals with recovering identical secrete keys at both ends.
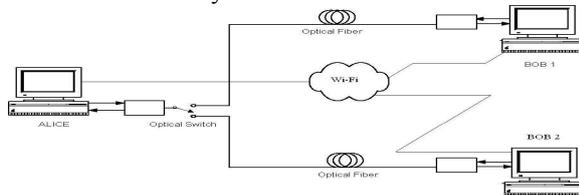

Figure 3. Simplified block diagram of a point-to-point QKD link in concept.

In terms of set up, as shown in Figure 4, the quantum channel is taking the task that using quantum cryptography to establish the key used for the encryption of user data in 802.11i, which is the TK.

When the quantum handshake completion the wireless Wi-Fi will either refuse the subscriber station to communicate data via the classical channel or take the subscriber station to access the Wi-Fi and the system becomes "normal" Wi-Fi working states, which will run the communications in the defined classical channels.

The quantum channel between Alice and Bob1 is shown in Fig. 4, the channel between Alice and Bob2 is similar. At Alice, laser pulses are generated by vertical cavity surface emitting lasers (VCSELs) and attenuated into single photon level. The polarization states of photons are set by polarizers according to corresponding protocol (B92 or BB84). Then

photons are combined and sent into a fiber through a non-polarizing beam splitter (NPBS).
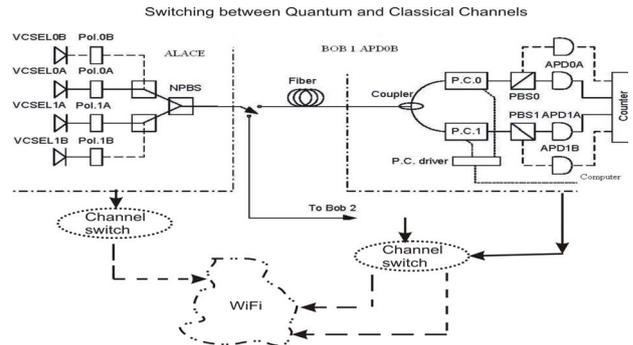

Figure 4. Quantum channel implementing by optical fibers: schematic diagram of the QKD system with PRAC sub-systems. VCSEL: Vertical Cavity Surface Emitting Laser ; Pol.: Polarizer; NPBS: Non-Polarizing beam splitter; P.C.: Polarization Controller; PBS: Polarizing beam splitter; APD: Silicon avalanche photodiode.

Then photons are combined and sent into a fiber through a non-polarizing beam splitter (NPBS). The polarizers Pol. 0A, 0B, 1A, and 1B are oriented to 0°, 90°, +45°, and -45° respectively. Only two channels, 0A and 1A, are used for B92, while all four channels are used for BB84. At Bob, polarization controllers recover the polarization state of photons to their original state at Alice. The 3-dB coupler randomly chooses the detection base and the polarization beam splitter (PBS) helps to determine the key value via an agent-oriented. Finally the photons are detected by single photon detectors (APDs). Two APDs, 0A and 1A, are used for B92, while four APDs are all used for BB84. The quantum bit error rate (QBER) for our experiment is 0.04 and due to modifications, i.e. most of the computations and bit comparisons are done in memory, the efficiency has been improved by 60%.

VI. Conclusions

Risks are inherent in wireless technology. Most significant source of risks in wireless networks is that the technology's underlying communication medium, the airwave, is open to intruders. Due to this reason a lot of efforts have been put to address security issues in wireless networks.

The advantage of quantum cryptography over traditional key exchange methods is that the exchange of information can be shown to be secure in a very strong sense, without making assumptions about the intractability of certain mathematical problems. In our work, we take advantage of the "unconditional security" offered by QKD to merge with IEEE 802.11i wireless network. For small wireless networks such as IEEE 802.11, quantum cryptography can serve better to provide secure data communications. Regarding the line of sight (LOS) problem occurring from the QKD to the wireless

networks, we have noted the there are three models can be discussed [20] namely, less scattered LOS short-rang indoor propagation environments, log-normal distributed channel, quasi-LOS links may be well modeled by Nakagami distributed channel and Gaussian distributed channel with highly-scattered outdoor NLOS propagation environments. Due to the conference paper size the analyses will be presented in another paper.

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