Quantum computing – What will be the real impact on 5G security?

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Agenda

- Introduction
- Quantum computing
- 5G security
- Impact I – symmetric crypto
- Impact II – asymmetric crypto
- A phased solution
- Conclusions

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Quantum computers

- In recent years there has been much discussion of the impact of quantum computing on cryptography.
- There is no general agreement that large-scale, general purpose, quantum computers will ever be built – see, for example, Dyakonov's March 2019 IEEE Spectrum article – but huge efforts continue.
- Should such computers ever become available, they will have a major impact on the security of today's cryptography.

Mobile security

- Security of mobile telecommunications has relied on cryptography since GSM, designed in the 1980s and first deployed in 1991.
- GSM is often referred to as **2G** for the **2nd generation** of mobile telecommunications.
- 5G is the latest generation, standardised by 3GPP, and 5G systems are now being deployed globally.
- Mobile comms are very widely used worldwide, and 5G looks set to become even more significant.
- So the security of 5G is hugely important.

Quantum and 5G

- These observations have motivated this talk, which examines the impact of quantum computing on 5G security.
- As I will describe, key parts of the system as currently specified are vulnerable should a quantum computer become available.
- This detailed analysis had led to the proposal of a phased upgrade to 5G security, with a smooth and simple migration path.

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General observations

- This review of priorities in 5G security evolution is just one amongst many needed.
- For every major application of cryptography a careful review of the impact of quantum computing needs to be done without delay.
- Such reviews should assess which parts of the system are vulnerable to quantum computing, and what the impact would be if these parts of the system are broken.

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Reviews needed

- Reviews should consider how long it will take:
  - to replace crypto used in each part of the system;
  - to update the specifications;
  - to produce replacement implementations; and
  - to replace all existing deployed implementations.
- The total time could be very considerable, e.g., credit and debit cards have a typical lifetime of three-five years, so replacing all such cards could take a decade or more (and this doesn't even consider the time required to replace the supporting infrastructure).

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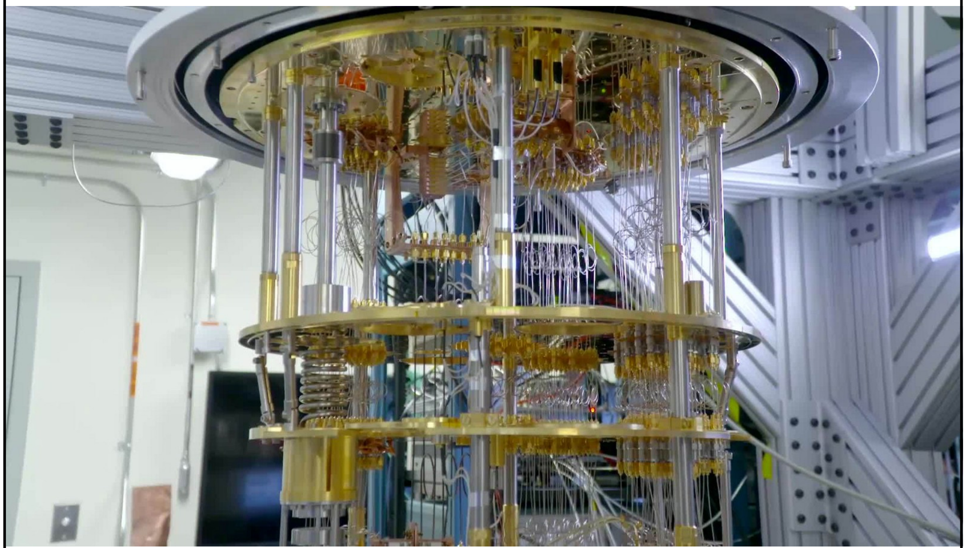

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Potential impact

- If and when they arrive, we cannot be sure of the precise performance in terms of:
  - number of quantum operations per second;
  - number of quantum bits available.
- However, we can estimate the complexity of certain computations in terms of the number of quantum logic gates.
- From crypto perspective, there are two key algorithms that have been devised to run on quantum computers.

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Shor's algorithm (1994)

- Greatly simplifies solving two problems, the hardness of which underlies all currently used asymmetric crypto:
  - factorising large integers;
  - computing discrete logarithms in elliptic curve or finite field multiplicative groups.
- Means that all currently used asymmetric algorithms are compromised for feasible key lengths.

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Grover's algorithm (1997)

- Suppose function *f* has |Domain(*f*)|=2^k.
- Reduces complexity of searching for solutions *x* to ***f*(*x*)=*y*, for known *y***, from 2^k function evaluations to $O(2^{k/2})$ function evaluations.
- A brute force key search (with known plaintext) involves solving such an equation.
- This effectively reduces key length for symmetric algorithms by half.
- Actually not so simple since function evaluation for AES involves lots of quantum computation.

Impacts

- For message authentication and digital signature applications a *just in time* approach is good enough.
- For applications involving encryption, or key establishment for encryption (e.g. TLS), an *as soon as possible* approach is warranted.

Replacing today's crypto

- For symmetric crypto, moving from 128-bit keys to 256-bit keys is more than adequate.
- For asymmetric crypto need new algorithms.
- Fortunately, NIST, ETSI, ISO/IEC and other standards bodies are working on it …
- The NIST *Post-Quantum Cryptography Standardization* competition is moving ahead – Round 2 candidates announced in January 2019.

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Principal actors

- The main players in 5G security are:
  - User Equipment (**UE**), made up of a Mobile Equipment (**ME**) and a **USIM** (chip card);
  - USIM issued by the **home network/issuing network**, which has an Authentication credential Repository and Processing Function (**ARPF**);
  - USIM and ARPF share a **128-bit secret key *K***;
  - UE gets service from a **visited network**, which has a Security Anchor Function (**SEAF**).

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Main security objectives

- 5G security is an evolution of 4G security, itself an evolution of 2G and 3G security.
- Like its predecessors, 5G security has three main aims, in decreasing order of importance:
  - *fraud prevention* (through USIM-network authentication);
  - *voice, data and signalling protection* between UE and visited network (using encryption and MACs);
  - *user identity privacy* against radio path eavesdroppers (through temporary identifiers).

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5G new features

- Three major differences between 4G and 5G:
  - *flexibility in authentication method* – USIM can authenticate to the serving network using either 5G AKA or the Internet EAP-AKA';
  - *robust mobile identity confidentiality* – using asymmetric encryption to supplement temporary IDs;
  - *data integrity protection* – all transmitted voice and data is integrity protected, not just signalling messages as in 4G.

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Security architecture

- Can divide the functioning of 5G crypto-based security into four main parts:
  - Authentication and Key Agreement (AKA);
  - Key derivation;
  - Session security;
  - Mobile identity confidentiality.
- Next summarise each of these (we only cover 5G AKA and not EAP-AKA').

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Authentication and Key Agreement (AKA)

- 5G AKA is an evolution of AKA in 2G, 3G and 4G – it is the foundation of 5G security.
- The home network ARPF generates **Authentication Vectors** (**AVs**) for its USIMs which are sent to the appropriate visited networks and used in 5G AKA protocol.
- AVs are computed using long-term key *K*.
- Avoids the need for the key *K* to ever leave the home network's ARPF or the USIM.

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Authentication Vectors I

5G AVs are computed in three stages.

1. Generate a 3G AV: **(RAND, XRES, CK, IK, AUTN)**
   – RAND is authentication challenge (network to USIM);
   – XRES is expected response (for authentication of USIM);
   – CK and IK are keys;
   – AUTN (authentication token) contains:
      - a 64-bit encrypted sequence number SQN (= SQN⊕AK);
      - a 48-bit MAC (for authentication of network to USIM).
   – All 128-bit values.
   – Computed using functions *f*1 – *f*5 (home-network-specific, although set of functions provided in 3GPP specifctions).

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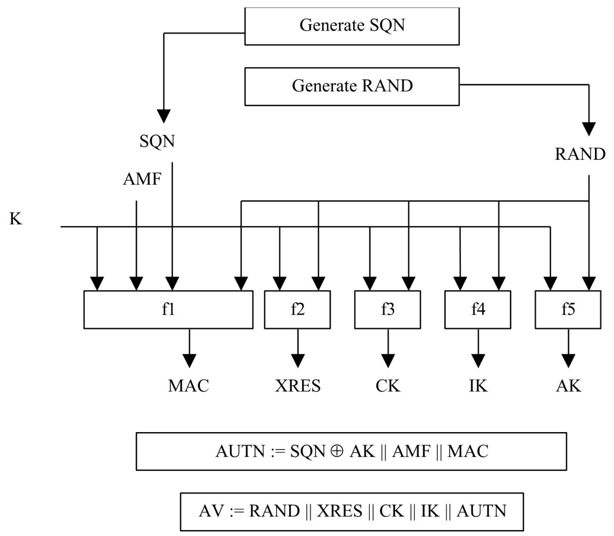
Authentication Vectors II



Authentication Vectors III

2. Derive a 5G HE AV **(RAND, AUTN, XRES*, K_{AUSF})** from the 3G AV:
   - XRES* = *f*(XRES, RAND, CK, IK, servingnetworkID);
   - K_{AUSF} = *f*(CK, IK, AUTN, servingnetworkID).
3. Compute a 5G AV **(RAND, AUTN, HXRES*, K_{SEAF})** from the 5G HE AV:
   - HXRES* = *f*(XRES*, RAND);
   - K_{SEAF} = *f*(K_{AUSF}, servingnetworkID).

- Step 2 is computed by the home network **outside the ARPF**.
- Step 3 is computed by the **serving network**, not the home network.

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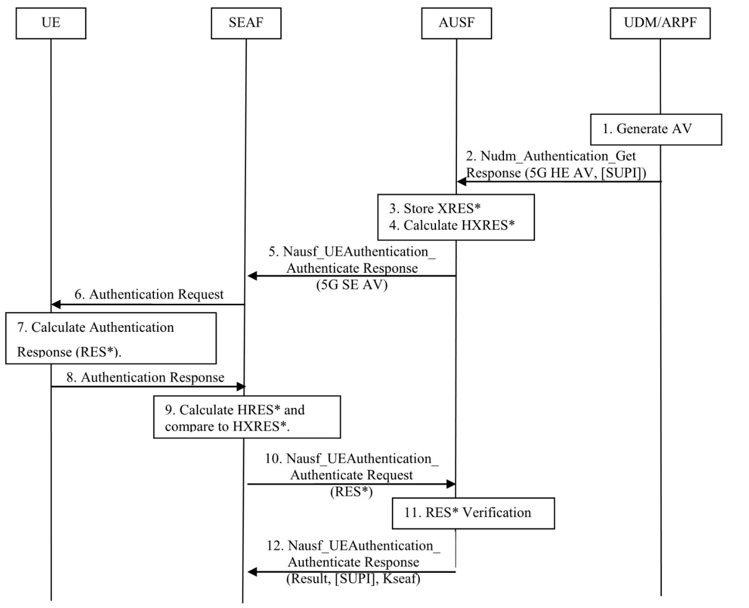

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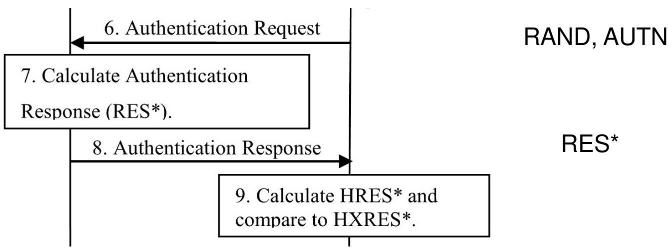
AKA protocol I

- In the diagram:
  - steps 1-5: computation and transfer of the 5G AV, and
  - steps 6-12: use of the AV in the AKA protocol.



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AKA protocol II

- The RAND and AUTN are passed to the **USIM** by the ME.
- The **USIM** essentially does the same job as done by the ARPF to compute the 3G AV.
- The SQN is decrypted and checked and the MAC is checked.
- If the checks work out, the **USIM** sends the ME the 3G-style RES, CK and IK.
- This is converted to the 5G RES* by the **ME** which is sent to the serving network. The **ME** also computes K_{SEAF}.
- The **serving network** converts RES* to HRES*, which is compared to the HXRES* value in the 5G AV.

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Key derivation

- A wide range of 128-bit operational keys are derived from the **anchor key** K_{SEAF}.
- These are all derived in pairs – one for encryption and one for MACing.
- Different keys are derived for (a) data/voice transfer, and (b) various types of signalling.
- These key derivations take place in the ME and the serving network.
- Key derivations use standardised functions.

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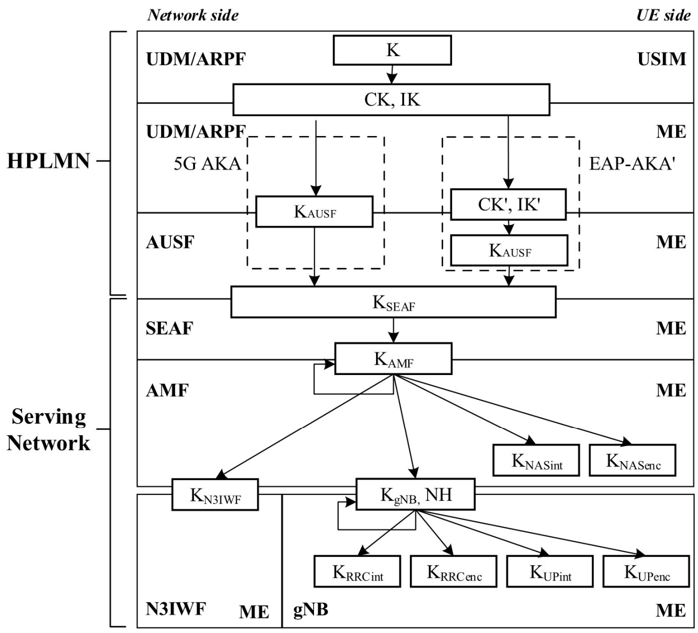

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Session security

- Data, voice and signalling sent between the UE and the visiting network are all encrypted and MAC-protected using 128-bit keys derived from K_{SEAF}.
- Unlike the USIM/ARPF functions *f*1 – *f*5, these algorithms are standardised (there are multiple options).
- [*Essentially, everything that goes on outside the USIM needs to be standardised.*]

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Backward compatibility

- It is important to note that:
  - the home network ARPF only outputs 3G AVs;
  - the USIM is only required to do 3G-style computations;
  - the 3G-style values of RES, CK and IK output by the USIM are used by the ME to derive 5G keys and the 5G authentication response.
- So a 3G USIM will work in a 4G or 5G handset.

Mobile identity encryption I

- As in previous generation networks, the primary method for identity confidentiality is the use of temporary identifiers (GUTIs).
- New GUTIs sent to the UE via an encrypted channel.
- However, *occasionally* the permanent identifier (SUPI) must be sent across the network.
- If so, it is asymmetrically encrypted using a randomised scheme of the home network's choice (although ECIES is provided as a possible scheme).
- The encrypted SUPI is sent to the home network which decrypts it and returns a cleartext value.

Mobile identity encryption II

- The encryption of the SUPI can be done either in the USIM or in the ME, at the choice of the USIM.
- Obviously, in the latter case then the standardised scheme must be employed and the USIM must provide the public key to be used.

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Keys and key derivation

- Foundation of all security (apart from mobile identity confidentiality) is a 128-bit key *K*.
- That is, all operational keys, as well as the authentication response RES* sent over the radio path, are a function of *K* and public data.
- Here 'public data' includes the RAND value, which is sent across the radio path in cleartext.

Proprietary functions

- Functions *f*1 – *f*5 are network-proprietary (possibly secret).
- This offers little additional security for two reasons:
  - candidate functions are standardised, and so at least some networks will use these public functions;
  - the functions must be built into every USIM, and hence could be obtained via reverse-engineering.

AKA

- Suppose a malicious party with a quantum computer has intercepted a matching pair of RAND and RES*.
- RES* (128 bits) is a (fixed, semi-public) function solely of RAND and *K* (128 bits).
- Grover's algorithm means that $O(2^{64})$ work is required to deduce *K*.

Session security

- A somewhat similar Grover-algorithm-based attack could be based on intercepted ciphertext.
- However, such an attack would require known plaintext and also knowledge of RAND.
- That is, such attacks are more difficult than those based on the AKA messages.
- Note that MACs are computed on plaintext prior to encryption, and hence so do not help.

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Attack impact

- Note that these attacks will only yield the long term key *K* for a single USIM, allowing cloning of this USIM and deriving of operational keys.
- That is, $O(2^{64})$ quantum operations will be needed to break a single USIM.
- 2^{64} computations is still a lot on a modern conventional computer, which have been developed over 70 years.
- Of course, if operator derives USIM keys from a 128-bit master key then all bets are off …

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When is a solution needed?

- Observe that USIMs potentially have a long lifetime.
- Unfortunately the attack can be performed using recorded RAND-RES* pairs, and so the problem should be fixed *as soon as possible*.
- Of course, switching USIMs is not so hard, but networks may wish to avoid encouraging users to switch USIMs lest they also switch network.

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Public key availability

- Mobile identity (SUPI) encryption can be performed in the ME, and in this case the ME needs to be given the public key by the USIM.
- That is any USIM must output the home network public key 'on demand'.
- So the public key is in the public domain.
- Even if the USIM does the SUPI encryption, the long-term public key will be in every USIM and so is prone to reverse-engineering attack.

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Shor's algorithm

- An opponent armed with a quantum computer can use Shor's algorithm to derive the home network private key from the public key.
- This will then re-enable *IMSI-catcher* attacks, where a fake network can ask a UE to reveal its permanent identity.
- This will apply to all UEs for that network.

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When is a solution needed?

- In principle this could be fixed *just in time* by replacing the asymmetric algorithm.
- This is because learning where a user was in the past is not so sensitive.
- You can't do IMSI-catching retrospectively.
- However, upgrading the algorithm without changing the USIM is likely to be tricky, so making the change as soon as possible would be highly desirable.

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A way forward

- Because of the way the system is designed, it seems possible to develop a three-phase approach to a post-quantum-secure 5G.
- This should allow a simple and smooth migration.
- Painful real-world experience says that a simple migration path is absolutely critical in practice.

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Phase 1: Long-term secret key

- Observe that the long-term secret key *K* never leaves the USIM or issuing network ARPF.
- The key *K* is only ever used as shown in the diagram.
- That is, it is only ever used as input to the functions *f*1 – *f*5.

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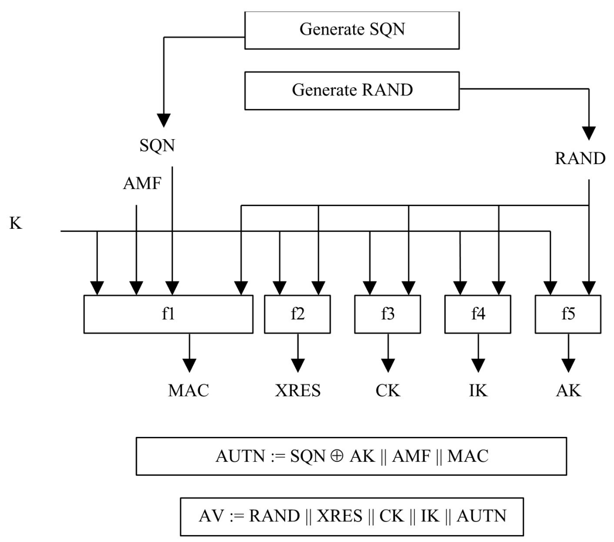
Use of the secret key *K*



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Implications of 256-bit key K

- Note that *f*1 – *f*5 are operator-specific.
- So a USIM equipped with a **256-bit key could be deployed with existing handsets and infrastructure today** – as long as the issuing network's ARPF is updated appropriately.
- Of course, new functions *f*1 - *f*5 will be needed, and the standards updated to allow this.

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What needs to be changed?

- Just a few simple changes are needed:
  - update the standards (probably only 3GPP TS 33.105) to permit longer keys;
  - update the standards to give requirements for *f*1 – *f*5 in case of a 256-bit key *K*;
  - update the standards to provide a new set of 'example' functions *f*1 – *f*5;
  - encourage operators and manufacturers to switch.

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How does it affect security?

- A 256-bit key will be post-quantum-secure (assuming functions designed with care).
- This prevents cloning of USIMs.
- Only remaining attack would be to discover derived 128-bit operational keys.
- Impact of such an attack would be small relative to the high per-key attack cost, since such keys are changed every few hours.

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Phase 2: Asymmetric encryption

- Asymmetric encryption/decryption only ever in the USIM, (optionally) the ME, and the home network.
- So, pending the availability of upgraded handsets, an operator **could switch to a post-quantum-secure scheme today**, assuming:
  - the availability of appropriate USIMs capable of performing the new encryption algorithm; and
  - necessary changes to the issuing network.
- Once a new encryption algorithm is standardised and implemented in handsets, the USIM can delegate encryption to the ME.

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What needs to be changed?

- The following changes will be needed:
  - selection of a post-quantum-secure asymmetric encryption algorithm, presumably once standards for such algorithms are available (e.g. from NIST);
  - inclusion of the scheme in the relevant standards;
  - at some point, the inclusion of this algorithm in handsets will need to be mandated;
  - encourage operators to adopt the scheme.

How does it affect security?

- Changing the algorithm will prevent compromise of the encrypted SUPI.
- This will restore mobile identity confidentiality to the status it has today.
- Sadly it is not 100% robust, as active error-message-based attacks are possible to link two appearances of the same UE.

Phase 3: Key derivation and use

- Currently, all operational keys (ultimately derived from CK and IK) are 128 bits long.
- Post-quantum-security will require changing all keys to 256 bits and upgrading all algorithms to use 256-bit keys.
- Fortunately:
  - all keys are derived from the combination of CK and IK (total of 256 bits), and
  - 256 bit keys are already derived at each stage (although only 128 of the 256 are actually used).

What needs to be changed?

- The following changes will be needed:
  - selection of appropriate 256-bit-key encryption and MAC functions;
  - inclusion of the new functions in the relevant standards;
  - mandating manufacturers and operators to implement these functions;
  - switching all these functions on – e.g. in 6G.
- No new USIMs needed (assuming already upgraded in Phase 1)!

How does it affect security?

- If:
  - all keys are 256 bits long, and
  - are derived from 256-bit keys (or equivalent);
  - key derivation functions are well-selected;
- then no quantum computer based attacks using Grover's algorithm will be possible.

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Summary of findings

- Have proposed a three-phase series of evolutionary changes to enable a post-quantum secure mobile network.
- The most significant changes will simultaneously make the 3G, 4G and 5G long-term secret key post-quantum secure.

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Summary of recommendations

- A three-phase sequence of upgrades is proposed:
  1. Switch to 256-bit USIM keys for all new USIMs **asap** – affects only USIMs and the ARPF (old USIMs will continue to work) – fixes 3G, 4G, 5G;
  2. Upgrade to post-quantum-secure asymmetric encryption – affects only USIMs, handsets and home networks – **when algorithms available**;
  3. **In long term** upgrade all symmetric algorithm keys to 256 bits – affects everything apart from USIMs and the ARPF.

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Good news

- Slightly bizarrely, 3GPP TS 33.501 (5G security architecture) already allows both 128-bit and 256-bit keys *K*, so moves are already afoot to switch.
- However, 3GPP TS 33.105, which specifies how *K* is used and also the requirements on *f*1 – *f*5, specifies only a 128-bit key.
- 256-bit key candidates for *f*1 – *f*5 have also been devised – called **TUAK** (see 3GPP TS 35.201).
- So Phase 1 is almost done, except for making the final changes to the standards and encouraging operators to get moving …

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Other news

- The functions used for key derivation (mainly based on SHA-256) have already been specified in such a way that moving to 256-bit keys throughout should be straightforward.
- Of course, network infrastructures and handsets will need to be upgraded to support algorithms using longer keys before the solution can be enabled.
- This seems a long way off.

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More information

- A preprint covering most of the material in this talk was recently posted to arXiv:
  - Chris Mitchell, *The impact of quantum computing on real-world security: A 5G case study*. arXiv:1911.07583v1 [cs.CR] 18 Nov 2019.
- All 3GPP specifications are available from the 3GPP website: http://www.3gpp.org