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Elemente der Mathematik

An application of Euclidean algorithm in cryptanalysis of RSA

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1 Introduction

Let p and q be two odd primes of the same size and $n = pq$. Consider integers e, d with $1 < e, d < \phi(n)$ such that $ed \equiv 1 \pmod{\phi(n)}$. Then (n, e) and d are the public and the private key, respectively, for a typical RSA public-key cryptosystem. The encryption and decryption algorithms are given by $C = M^e \bmod n$ and $M = C^d \bmod n$, respectively. In order to accelerate the operations involving the private key d in some devices, like for

Nachdem 1976 Whitfield Diffie und Martin Hellman das Schlüsseltauschproblem der Kryptologie gelöst hatten, folgte 1977 mit dem RSA-Kryptosystem von Rivest, Shamir and Adleman das erste veröffentlichte asymmetrische Verschlüsselungsverfahren. Dieses besitzt eine Reihe von praktischen Anwendungen, die z.B. in Web-Browsern und Chip-Karten eingesetzt werden. Das RSA-Verfahren beruht auf dem Produkt $n = pq$ von zwei ähnlich grossen Primzahlen und zwei ganzen Zahlen e und d für die $1 < e, d < \phi(n)$ und $ed \equiv 1 \mod \phi(n)$ gilt, wobei ϕ die Eulersche Phi-Funktion bezeichnet. Öffentlich bekannt sind nur der Parameter n und der öffentliche Schlüssel e. Die Nachricht M wird durch $C = M^e \bmod n$ verschlüsselt, und mit dem privaten Schlüssel d via $M = C^d \bmod n$ entschlüsselt. Um das Verfahren zu brechen muss ein Angreifer die Faktoren von n finden. In der vorliegenden Arbeit wird der Fall betrachtet, wo e und n von derselben Grössenordnung sind, und wo eine der Zahlen $k = (ed-1)/\phi(n)$ und $e-k$ höchstens ein Viertel der Bitlänge von e hat. Die Anwendung des erweiterten euklidischen Algorithmus' liefert dann ein effizientes und einfaches deterministisches Verfahren um n zu faktorisieren und somit den privaten Schlüssel d in $O((\log n)^2)$ Operationen zu bestimmen.

example a smart card, one might use a short secret exponent. On the other hand, in 1990, Wiener [16] proposed a polynomial time algorithm for breaking a typical RSA cryptosystem provided that $d < n^{1/4}/3$. In this case, d is the denominator of some convergent of the continued fraction expansion of e/n. The computation of the continued fraction expansion of e/n needs time $O((\log n)^2)$ bit operations and the total number of convergents is of order $O(\log n)$. Since Wiener's approach for testing convergents requires time $O((\log n)^2)$, the overall time complexity of Wiener's attack is $O((\log n)^3)$ bit operations (it is usually needed to check the last convergents). In [8, Section 5], Wiener's attack is presented as a bivariate linear equation problem and one can find d via a shortest vector computation in a two-dimensional lattice in time $O((\log n)^2)$.

Extensions of Wiener's attack that allows the RSA cryptosystem to be broken when d is a few bits longer than $n^{1/4}$ are described in [4, 5, 13, 14]. Furthermore, attacks based on Coppersmith's lattice-based technique for finding small roots of modular polynomials equations using the LLL-algorithm are proposed in [1, 3] in case where e is very close to n. These lattice attacks are applicable provided that $d < n^{0,292}$. Note however that these attacks are not rigorous and so this bound is not strictly proved. Finally, some other extensions of Wiener's attack are described in [1, 9, 10, 11, 15].

In 2004, Hinek [7] proved that, in case where $\sqrt{6}(\phi(n) - d) < n^{1/4}$, Wiener's attack works. Furthermore, he showed that if the attacks in [1, 3] work for all $d < n^{\delta}$, then the attacks also work for $d > \phi(n) - n^{\delta}$.

In this note, we consider the case where the public exponent e has the same order of magnitude as n and one of the integers $k = (ed - 1)/\phi(n)$ and $e - k$ has at most one-quarter as many bits as e. Using the equation $ed - k\phi(n) = 1$ and the extended Euclidean algorithm, we describe an efficient simple deterministic algorithm for the computation of the factorization of n in time $O((\log n)^2)$ bit operations. Since k has at most one-quarter as many bits as e if and only if d has at most one-quarter as many bits as n, we see that our hypothesis is equivalent to that of Wiener's.

The paper is organized as follows. In Section 2 we present our results and we describe our attack. Section 3 is devoted to the proof of our results. Finally, an example is given in Section 4. Finally, Section 5 concludes the paper.

2 An attack based on Euclidean algorithm

Let p and q be two odd primes of the same bit-size ℓ and $n = pq$. Consider positive integers e, d with $1 < e, d < \phi(n)$ such that $ed \equiv 1 \pmod{\phi(n)}$. Then (n, e) is the public key and d the private key for an RSA cryptosystem. Set $a = n + 1 \bmod e$ and $\Delta = \gcd(e, a)$. The extended Euclidean algorithm for e and a gives integers $q_i > 0$ $(i = 1, \ldots, m)$ and r_i $(i = 0, \ldots, m + 1)$ such that $r_0 = e$, $r_1 = a$, $r_m = \Delta$, $r_{m+1} = 0$ and

$$r_{i-1} = r_i q_i + r_{i+1}, \quad 0 < r_{i+1} < r_i.$$

Further, there are integers s_i, t_i with $|t_i| < e/r_{i-1}$ and $|s_i| < a/r_{i-1}$ satisfying

$$s_i e + a t_i = r_i, \quad (i = 2, \ldots, m + 1)$$

(see [12]). Set $\mu_i = \gcd(t_i, r_i)$ and $t_i' = t_i/\mu_i$ $(i = 0, \ldots, m + 1)$. Our attack is based on the following result:

Theorem 1 *Let $e > n/c$, where c is an integer ≥ 1, and $k = (ed-1)/\phi(n)$. Suppose that k or $e-k$ is $\leq e^{1/4}/6\sqrt{c}$. Then, we have $\Delta < e^{3/4}$, and $k = |t'_j|$, $p+q = (a+|t'_j|^{-1}) \bmod e$ or $k = e - |t'_j|$, $p+q = (a+(e-|t'_j|)^{-1}) \bmod e$, respectively, where j is such that r_j is the largest remainder $< e^{3/4}$.*

Theorem 1 yields the design of the following deterministic algorithm for the computation of the factorization of n:

EUCLID-ATTACK
Input: An RSA public key (n, e) with $e > n/c$.
Output: The primes p and q.

1. Compute $a = (n+1) \bmod e$.
2. Using the extended Euclidean algorithm for e and a, compute the biggest remainder r_j among them which are $< e^{3/4}$ and the associated integers s_j, t_j such that $s_j e + a t_j = r_j$.
3. Compute $\mu_j = \gcd(t_j, r_j)$ and next $t'_j = t_j/\mu_j$.
4. Compute $\beta_1 = (a + |t'_j|^{-1}) \bmod e$ and next the solutions u_1 and v_1 of equation $X^2 - \beta_1 X + n = 0$. If u_1 and v_1 are positive integers, then output (u_1, v_1). Otherwise, go to the next step.
5. Compute $\beta_2 = (a+(e-|t'_j|)^{-1}) \bmod e$ and next the solutions u_2 and v_2 of equation $X^2 - \beta_2 X + n = 0$. If u_2 and v_2 are positive integers, then output (u_2, v_2). Otherwise, output FAIL.

Theorem 2 *Let $e > n/c$, where c is a positive integer, and $k = (ed-1)/\phi(n)$. Suppose that k or $e-k$ is $\leq e^{1/4}/6\sqrt{c}$. Then the above algorithm computes correctly the primes p and q in time $O((\log e)^2)$ bit operations.*

In order to avoid the attacks to small decryption exponent, a class of RSA encryption exponents e with corresponding $k = e - 1$ is analysed in [6]. In this case the decryption exponent d is $\geq 2\phi(n)/3$. Since $k = e - 1$, Theorem 2 yields that the computation of the factorization of n, and so the computation of d, can be easily achieved.

Suppose now that $n/(c-1) > e > n/c$ with $c \geq 2$. We have:

$$\frac{d}{k} = \frac{ed}{ek} = \frac{k\phi(n)+1}{ek} < \frac{n-1}{e} + \frac{1}{ek} < c.$$

If $k \leq e^{1/4}/6\sqrt{c}$, then we obtain:

$$d < kc \leq \frac{\sqrt{c}\, e^{1/4}}{6} < \frac{\sqrt{c}}{6(c-1)^{1/4}} n^{1/4}.$$

Thus, for $c = 10$, we get $d < n^{1/4}/3$. On the other hand, we have:

$$k = \frac{ed-1}{\phi(n)} < \frac{ed}{\phi(n)} < \frac{2ed}{n} < \frac{2}{c-1} d.$$

If $d < n^{1/4}/3$, then we deduce:

$$k < \frac{2}{c-1} d < \frac{2e^{1/4}}{3(c-1)^{3/4}},$$

and so, for $c \geq 19$, we get $k \leq e^{1/4}/6\sqrt{c}$. Thus, we see that the efficacy of our approach is comparable with that of Wiener's method. Furthermore, as we have mentioned in the Introduction, Wiener's method needs $O((\log n)^3)$ bits operations while our approach $O((\log n)^2)$.

The solutions of the linear Diophantine equation $dx - y\phi(n) = 1$ are $x(T) = e + T\phi(n)$ and $y(T) = k + Td$, where $T \in \mathbb{Z}$. Consider now the inequalities:

$$6^4(k + Td)^4 < (e + T\phi(n)) \quad \text{and} \quad 6^4(e - k + T(\phi(n) - d))^4 < (e + T\phi(n)).$$

We remark that for T large enough, for instance $T > \phi(n)^{1/3}$, the above inequalities are not satisfied. Thus, in case that we replace the public key e by $x(T) = e + T\phi(n)$ with $T > \phi(n)^{1/3}$ our attack does not work. Note that Wiener's attack is not guaranteed to work if $e > n^{1.5}$ and the attack of [1] is effective as long as $e < n^{1.875}$.

3 Proof of Theorems 1 and 2

Proof of Theorem 1. First, we give the proof of Theorem 1. The equalities $ed - k\phi(n) = 1$ and $\phi(n) = n - (p + q) + 1$ yield:

$$ed - 1 = k(n - (p + q) + 1),$$

whence, we obtain:

$$k(n + 1 - (p + q)) + 1 \equiv 0 \pmod{e}.$$

Setting $y_0 = k$ and $x_0 = p + q$, we get:

$$1 + ay_0 - x_0y_0 \equiv 0 \pmod{e}.$$

Suppose that $p < q$. Then $p < \sqrt{n}$. Since p and q have the same size ℓ, we have:

$$2^{\ell-1} + 1 \leq p < q \leq 2^{\ell-1} + \cdots + 1.$$

Thus, we get:

$$q - p \leq 2^{\ell-2} + \cdots + 2 < 2^{\ell-1} + 1 \leq p,$$

whence we obtain $q < 2p$. Therefore, we have:

$$x_0 = p + q < 3\sqrt{n} < 3\sqrt{ce}.$$

Suppose that $y_0 \leq e^{1/4}/6\sqrt{c}$. If $\Delta \geq e^{3/4}$, then we have $x_0y_0 \equiv 1 \pmod{\Delta}$ and

$$|x_0y_0 - 1| < e^{3/4} \leq \Delta.$$

It follows that $x_0y_0 = 1$, whence we get $x_0 = y_0 = 1$ which is a contradiction. Hence $\Delta < e^{3/4}$. Let r_j be the bigger among the remainders which are $< e^{3/4}$. Then, we have $r_{j-1} > e^{3/4}$ and $|t_j| < e/r_{j-1} < e^{1/4}$. Further, we have:

$$t_j(1 + ay_0 - x_0y_0) + s_jey_0 \equiv 0 \pmod{e},$$

whence we get:

$$0 \equiv t_j + (t_ja + s_je)y_0 - t_jx_0y_0 \equiv t_j + r_jy_0 - t_jx_0y_0 \pmod{e}.$$

Set $f(x, y) = t_j + r_jy - t_jxy$. Then, we have $e \mid f(x_0, y_0)$ and

$$|f(x_0, y_0)| < e^{1/4} + \frac{e}{6\sqrt{c}} + \frac{e}{2} < e.$$

It follows that $f(x_0, y_0) = 0$, and so, we obtain:

$$t'_j + r'_jy_0 - t'_jx_0y_0 = 0.$$

It follows that $t'_j \mid r'_jy_0$. Since $\gcd(t'_j, r'_j) = 1$, we obtain $t'_j \mid y_0$. Furthermore, the above equality implies that $y_0 \mid t'_j$. Therefore, we have $y_0 = |t'_j|$. Thus, the congruence $1 + ay_0 - x_0y_0 \equiv 0 \pmod{e}$ yields $x_0 = (a + |t'_j|^{-1}) \bmod e$.

Set $z_0 = -y_0 \bmod e$. Suppose that $z_0 \leq e^{1/4}/6\sqrt{c}$. If $\Delta \geq e^{3/4}$, then we deduce $1 + x_0z_0 \equiv 0 \pmod{\Delta}$ and

$$|x_0z_0 + 1| < 1 + \frac{e^{3/4}}{2} < \Delta.$$

It follows that $x_0z_0 + 1 = 0$ which is a contradiction. Thus, we get $\Delta < e^{3/4}$. Now, working as previously, we have:

$$1 - az_0 + x_0z_0 \equiv 0 \pmod{e}$$

and we deduce that $z_0 = |t'_j|$. Therefore $e - y_0 = |t'_j|$. It follows that $x_0 = (a + (e - |t'_j|)^{-1}) \bmod e$.

Proof of Theorem 2. The proof of correctness of the algorithm EUCLID-ATTACK is a simple consequence of Theorem 1. We shall compute its time complexity following [12]. The execution of the extended Euclidean algorithm in Step 2 needs $O((\log e)^2)$ bit operations. The computation of δ and t'_j in Step 3 requires $O((\log e)^2)$ bit operations. Similarly, the computation of b_1 and b_2 needs $O((\log e)^2)$ bit operations. Finally, the solution of the quadratic equations in Steps 4 and 5 requires also $O((\log e)^2)$ bit operations. Therefore the time complexity of the algorithm EUCLID-ATTACK is $O((\log e)^2)$ bit operations.

4 A toy example

In this section we give an example of application of our algorithm. Let

$$p = 9223372036854777017 \quad \text{and} \quad q = 9224497936761618437$$

be two 64-bits primes. Their product is the number

$$n = 85080976323951696719635578579671062429.$$

We compute:

$$\phi(n) = (p-1)(q-1) = 85080976323951696701187708606054666976.$$

We select:

$$d = \phi(n) - 2^{22} - 2^{14} - 2^{6} - 2^{3} - 1 = 85080976323951696701187708606050456215$$

and compute:

$$e = d^{-1} \bmod \phi(n) = 61100559406251463256709716070302151015.$$

Thus (n, e) and d is the public and private key for an RSA scheme. We shall use the algorithm EUCLID-ATTACK in order to compute the factorization of n.
First, we compute

$$a = (n+1) \bmod e = 23980416917700233462925862509368911415.$$

We apply the Euclidean algorithm for $r_0 = e$ and $r_1 = a$, and we compute the remainders $r_2, r_3, \ldots$. The biggest remainder which is smaller than $e^{3/4}$ is

$$r_{13} = 55785270375887536485564215.$$

The corresponding pair (s_{13}, t_{13}) is the pair $(-1186820, 3023941)$.
Further, we have $\gcd(r_{13}, t_{13}) = 1$. Following the steps of the algorithm, we compute:

$$b_1 = a + t_{13}^{-1} \bmod e = 47960833835400466907403855045121427376.$$

We solve the equation $x^2 - b_1 x + n = 0$ and we see that their solutions are not integers. Next, we compute

$$b_2 = a + (e - t_{13})^{-1} \bmod e = 18447869973616395454.$$

The solutions of the equation $x^2 - b_2 x + n = 0$ are the primes p and q. Note that $2e > n$ and so, $c = 2$. Furthermore, we have $n - k < e^{1/4}/6\sqrt{2}$.

5 Conclusion

In this paper, we have presented a new attack on the RSA cryptosystem based only on the extended Euclid algorithm. It computes the factorization of n in deterministic time $O((\log n)^2)$ bit operations, in the case where the public exponent e has the same order of magnitude as n and one of the integers $k = (ed-1)/\phi(n)$ and $e - k$ has at most one-quarter as many bits as e. Comparing with Wiener's classical attack and its presentation as a bivariate linear equation problem, our attack is quite simpler, since it avoids the use of continuous fractions and lattices. Its efficiency is comparable to that of Wiener's attack, and its time complexity the same as that of the solution of the corresponding bivariate linear equation problem but better than that of the classical Wiener attack.

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