

Ex1

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1 Estruturas Criptográficas - Criptografia e Segurança da Informação

Grupo 03

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1.1 TP4 - Exercício 1

Implemente um protótipo do esquema descrito no “draft” FIPS 204 que deriva do algoritmo Dilithium.

1.2 Resolução

Para a resolução deste exercício, foi implementado um protótipo do esquema descrito no “draft” FIPS 204 que deriva do algoritmo Dilithium. Informações extra sobre as funções implementadas podem ser encontradas no papel de especificação do esquema de assinaturas que se encontra na pasta [docs](#).

1.2.1 Bibliotecas Utilizadas

Esta secção é dedicada ao import das bibliotecas necessárias para a realização do exercício.

```
[ ]: import time
      from sage.all import *
      import hashlib
```

1.2.2 Funções Auxiliares

Esta secção contém as funções auxiliares que foram utilizadas para a resolução do exercício 1.

```
[ ]: def bits_to_integer(y):
      alpha = len(y)
      x = 0
      for i in range(1, alpha + 1):
          x = y[alpha - i] + 2 * x
      return x
```

```

def bits_to_bytes(y):
    c = len(y)
    num_bytes = ceil(c / 8)
    z = [0] * num_bytes
    for i in range(c):
        z[i // 8] = z[i // 8] + y[i] * 2**(i % 8)
    return z

def bit_reverse(x, bits):
    y = 0
    for i in range(bits):
        y = (y << 1) | (x & 1)
        x >>= 1
    return y

def bytes_to_bits(z):
    d = len(z)
    y = [0] * (d * 8)
    for i in range(d):
        for j in range(8):
            y[8*i + j] = z[i] % 2
            z[i] = z[i] // 2
    return y

def bitlen(x):
    return Integer(x).nbits()

def simple_bit_pack(w, b):
    z = []
    for i in range(256):
        z = z+integer_to_bits(w[i], bitlen(b))
    return bits_to_bytes(z)

def simple_bit_unpack(v, b):
    c = bitlen(b)
    z = bytes_to_bits(v)
    w = [0] * 256
    for i in range(256):
        # BitsToInteger((z[ic], z[ic + 1], . . . z[ic + c - 1]), c)
        w[i] = bits_to_integer(z[i*c:(i+1)*c])
    return w

def bit_pack(w, a, b):
    z = []
    for i in range(256):
        z = z+integer_to_bits(b - w[i], bitlen(a + b))
    return bits_to_bytes(z)

```

```

def bit_unpack(v, a, b):
    c = bitlen(a+b)
    z = bytes_to_bits(v)
    w = []
    for i in range(256):
        wi = b - bits_to_integer(z[i*c:(i+1)*c])
        w.append(wi)
    return w

def H1024(input_bytes):
    hash_output = hashlib.sha256(input_bytes).digest()
    concatenated_output = hash_output
    while len(concatenated_output) < 128:
        hash_output = hashlib.sha256(hash_output).digest()
        concatenated_output += hash_output
    concatenated_output = concatenated_output[:128]

    bit_array = []
    for byte in concatenated_output:
        bits = bin(byte)[2:].zfill(8)
        bit_array.extend(int(bit) for bit in bits)

    return bit_array

def integer_to_bits(x, alpha):
    y = [0] * alpha
    for i in range(alpha):
        y[i] = Integer(x) % Integer(2)
        x = x // 2
    return y

def coef_from_three_bytes(b0, b1, b2, q):
    if b2 > 127:
        b2 -= 128
    z = 2 ** 16 * b2 + 2 ** 8 * b1 + b0
    if z < q:
        return z
    else:
        return None

def coef_from_half_byte(b, n):
    if n == 2 and b < 15:
        return 2 - (b % 5)
    elif n == 4 and b < 9:
        return 4 - b
    else:

```

```

        return None

def rej_ntt_poly(seed, q):
    a_hat = [None] * 256
    j = 0
    c = 0
    hsh=bits_to_bytes(H1024(bytearray(seed)))
    while j < 256:
        a_hat[j] =
    ↪coef_from_three_bytes(hsh[c%128],hsh[(c+1)%128],hsh[(c+2)%128],q)
        c += 3
        if a_hat[j] is not None:
            j += 1
    return a_hat

def rej_bounded_poly(seed, q, n):
    a = [0] * 256
    j = 0
    c = 0
    hsh=bits_to_bytes(H1024(bytearray(seed)))
    while j < 256:
        z = hsh[c%128]
        z0 = coef_from_half_byte(z % 16, n)
        z1 = coef_from_half_byte(z // 16, n)
        if z0 is not None:
            a[j] = z0
            j += 1
        if z1 is not None and j < 256:
            a[j] = z1
            j += 1
        c += 1
    return a

def expand_a(p, q, k, l):
    A_hat = [[None for _ in range(l)] for _ in range(k)]
    for r in range(k):
        for s in range(l):
            bits_s = integer_to_bits(s, 8)
            bits_r = integer_to_bits(r, 8)
            combined_bytes = bytearray(p) + bytearray(bits_s) +
    ↪bytearray(bits_r)
            A_hat[r][s] = rej_ntt_poly(combined_bytes, q)[s]
    return A_hat

def expand_s(p, l, k,q,n):
    s1 = [rej_bounded_poly(p + integer_to_bits(r, 16),q,n) for r in range(l)]

```

```

    s2 = [rej_bounded_poly(p + integer_to_bits(r + 1, 16), q, n) for r in
↪range(k)]
    return (s1, s2)

def polynomial_mul(a, b, q):
    return [(a[i] * b[i]) % q for i in range(len(a))]

def ntt(w, q):
    w_hat = [0 for _ in range(256)]
    for j in range(256):
        w_hat[j] = w[j]
    z=1753
    k = 0
    length = 128
    while length >= 1:
        start = 0
        while start < 256:
            k += 1
            zeta = Integer(z**bit_reverse(k, 8)) % Integer(q)
            for j in range(start, start + length):
                t = zeta * w_hat[j + length]
                w_hat[j + length] = (w_hat[j] - t)
                w_hat[j] = (w_hat[j] + t) % q
            start += 2 * length
        length = length // 2
    return w_hat

def ntt_inverse(w_hat, q):
    w = [0 for _ in range(256)]
    for j in range(256):
        w[j] = w_hat[j]
    z=1753
    k = 256
    length = 1
    while length < 256:
        start = 0
        while start < 256:
            k -= 1
            zeta = (-1 * Integer(z**bit_reverse(k, 8))) % Integer(q)
            for j in range(start, start + length):
                t = w[j]
                w[j] = (t + w[j + length])
                w[j + length] = (t - w[j + length])
                w[j + length] = zeta * w[j + length]
            start += 2 * length
        length *= 2
    f = 8347681

```

```

    for j in range(256):
        w[j] = f * w[j] % q
    return w

def mod_plus_minus(m, alpha):
    m_prime = Integer(m) % Integer(alpha)
    if m_prime > alpha // 2:
        m_prime -= alpha
    return m_prime

def power2_round(r, q, d):
    r_plus = Integer(r) % Integer(q)
    r0 = mod_plus_minus(r_plus, 2**d)
    r1 = (r_plus - r0) // (2**d)
    return (r1, r0)

def pk_encode(p, t1, q, d, k):
    pk = bits_to_bytes(p)
    max_value = (2 ** (bitlen(q - 1) - d)) - 1
    for i in range(k):
        pk += simple_bit_pack(t1[i], max_value)
    return pk

def pk_decode(pk, q, d, k):
    y = pk[:32]
    len_z = 32*(bitlen(q - 1)-d)
    z=[]
    for i in range(k):
        z.append(pk[32+i*len_z:32+(i+1)*len_z])
    p = bytes_to_bits(y)
    max_value = (2 ** (bitlen(q - 1) - d)) - 1
    t = [None for _ in range(k)]
    for i in range(k):
        t[i] = simple_bit_unpack(z[i], max_value)
    return p, t

def sk_encode(p, K, tr, s1, s2, t0, d, n):
    sk = bits_to_bytes(p) + bits_to_bytes(K) + bits_to_bytes(tr)
    for si in s1:
        sk = sk + bit_pack(si, n, n)
    for si in s2:
        sk = sk + bit_pack(si, n, n)
    for ti in t0:
        sk = sk + bit_pack(ti, (2**(d-1))-1, 2**(d-1))
    return sk

def sk_decode(sk, d, n, l, k):

```

```

f = sk[:32]
g = sk[32:64]
h = sk[64:128]
a_len = 32 * bitlen(2*n)
y=[]
for i in range(1):
    y.append(sk[128+i*a_len:128+(i+1)*a_len])
z=[]
for i in range(k):
    z.append(sk[128+l*a_len+i*a_len:128+l*a_len+(i+1)*a_len])
w_len = 32*d
w=[]
for i in range(k):
    w.append(sk[128+(l+k)*a_len+i*w_len:128+(l+k)*a_len+(i+1)*w_len])
p = bytes_to_bits(f)
K = bytes_to_bits(g)
tr = bytes_to_bits(h)
s1 = [bit_unpack(yi, n, n) for yi in y]
s2 = [bit_unpack(zi, n, n) for zi in z]
t0 = [bit_unpack(wi, (2**(d-1))-1, 2**(d-1)) for wi in w]
return p, K, tr, s1, s2, t0

def matrix_mutl(m_a,m_b,q):
    m_c = [[0 for _ in range(len(m_b[0]))] for _ in range(len(m_a))]
    for i in range(len(m_a)):
        for j in range(len(m_b[0])):
            for k in range(len(m_b)):
                m_c[i][j] += m_a[i][k] * m_b[k][j]
            m_c[i][j] %= q
    return m_c

def decompose(r,q,y2):
    r_plus = Integer(r) % Integer(q)
    r0 = mod_plus_minus(r_plus,(2*y2))
    if r_plus - r0 == q - 1:
        r1 = 0
        r0 = r0 - 1
    else:
        r1 = (r_plus - r0) // (2*y2)
    return (r1, r0)

def high_bits(r,q,y2):
    (r1,r0) = decompose(r, q, y2)
    return r1

def low_bits(r,q,y2):
    (r1,r0) = decompose(r, q, y2)

```

```

    return r0

def expand_mask(seed, mu, l, gamma_1):
    c = 1 + bitlen(gamma_1-1)
    s = [None for _ in range(l)]
    for r in range(l):
        n = integer_to_bits(mu+r, 16)
        v = [None for _ in range(32*c)]
        byts = bits_to_bytes(H1024(bytearray(seed+n)))
        for i in range(32*c):
            v[i] = byts[(32*r*c + i)%128]
        s[r] = bit_unpack(v, gamma_1 - 1, gamma_1)
    return s

def w1_encode(w1, k, q, y2):
    w1_tilde = []
    for i in range(k):
        w1_tilde = w1_tilde + bytes_to_bits(simple_bit_pack(w1[i], Integer(((q - 1) / (2 * y2)) - 1))))
    return w1_tilde

def sample_in_ball(seed, tau):
    c = [0 for _ in range(256)]
    k = 8
    for i in range(256 - tau, 256):
        while bits_to_bytes(H1024(bytearray(seed)))[k%128] > i:
            k += 1
        j = bits_to_bytes(H1024(bytearray(seed)))[k%128]
        c[i] = c[j]
        c[j] = (-1) ** (H1024(bytearray(seed))[i+tau-256])
        k += 1
    return c

def make_hint(z, r, q, y2):
    r1 = high_bits(r,q,y2)
    v1 = high_bits(r + z,q,y2)
    if r1 != v1:
        return 1
    return 0

def use_hint(h, r, q, gamma_2):
    m = (q - 1) // (2 * gamma_2)
    r1,r0 = decompose(r, q, gamma_2)
    if h==1 and r0 > 0:
        return (r1 + 1) % m
    elif h==1 and r0 <= 0:
        return (r1 - 1) % m

```



```

else:
    return r1

def hint_bit_pack(h, omega, k):
    y = [0] * (omega + k)
    index = 0
    for i in range(k):
        for j in range(256):
            if h[i][j] != 0:
                y[index] = j
                index += 1
        y[omega + i] = index
    return y

def sig_encode(c_til, z, h, l, y1, omega, k):
    o = bits_to_bytes(c_til)
    for i in range(l):
        o = o + bit_pack(z[i], y1 - 1, y1)
    o = o + hint_bit_pack(h, omega, k)
    return o

def hint_bit_unpack(y, k, omega):
    h = [[0]*256 for _ in range(k)]
    index = 0
    for i in range(k):
        if y[omega + i] < index or y[omega + i] > omega:
            return None
        while index < y[omega + i]:
            h[i][y[index]] = 1
            index += 1
    while index < omega:
        if y[index] != 0:
            return None
        index += 1
    return h

def sig_decode(o, y1, lbd, l, k, omega):
    lbd = lbd // 4
    w = o[:lbd]
    x = []
    for i in range(l):
        x.append(o[lbd + 32*(1+bitlen(y1-1))*i:lbd + 32*(1+bitlen(y1-1))*(i+1)])
    y = o[lbd + l*32*(1+bitlen(y1-1)):]
    c_til = bytes_to_bits(w)
    z = [None for _ in range(l)]
    for i in range(l):

```

```

        z[i] = bit_unpack(x[i], y1 - 1, y1)
    h = hint_bit_unpack(y,k,omega)
    return c_til, z, h

```

1.2.3 Geração de chaves

Função para gerar chaves públicas e privadas para utilização no esquema de assinaturas Dilithium.

```

[ ]: def ML_DSA_KeyGen(k, l, q, d, n):
    eps = [randint(0, 1) for _ in range(256)]
    print('eps:',eps)

    H_output = H1024(bytearray(eps))
    p = H_output[:256]
    p_ = H_output[256:768]
    K = H_output[768:]
    print('p:',p)
    print('p_:',p_)
    print('k:',K)

    A_hat = expand_a(p, q, k, l)
    print('A_hat:',A_hat)

    s1, s2 = expand_s(p_, l, k,q,n)
    print('s1:',s1)
    print('s2:',s2)

    NTT_s1 = []
    for i in range(l):
        s1_poly = PolynomialRing(Zmod(q), 'x')(s1[i])
        NTT_s1.append(NTT(s1_poly, q))
    A_NTT_s1 = matrix_mul(A_hat, NTT_s1, q)
    t = [NTT_inverse(PolynomialRing(Zmod(q), 'x')(A_NTT_s1_row), q) for
↪A_NTT_s1_row in A_NTT_s1]
    for i in range(k):
        for j in range(256):
            t[i][j] = (t[i][j] + s2[i][j])
    print('t:',t)

    t1, t0 = [], []
    for tt in t:
        tt1, tt0 = [], []
        for ti in tt:
            t1i, t0i = power2_round(ti, q, d)
            tt1.append(t1i)
            tt0.append(t0i)

```

```

        t1.append(tt1)
        t0.append(tt0)
    print('t1:',t1)
    print('t0:',t0)

    pk = pk_encode(p, t1, q, d,k)
    print('pk:',pk)
    print('pk size:',len(pk))
    print('expected size:',32+32*k*(bitlen(q-1)-d))

    tr = H1024(bytearray(pk))[:512]
    print('tr:',tr)

    sk = sk_encode(p, K, tr, s1, s2, t0, d, n)
    print('sk:',sk)
    print('sk size:',len(sk))
    print('expected size:',32+32+64+32*((1+k)*bitlen(2*n)+k*d))

    return pk, sk

```

```

[ ]: # Parameters
q = 8380417
d = 13
tau = 39
Tq = 128
gamma_1 = 2**17
gamma_2 = (q - 1) // 88
k = 4
l = 4
n = 2
beta = 78
omega = 80

pk, sk = ML_DSA_KeyGen(k, l, q, d, n)
print('pk:',pk)
print('sk:',sk)

```

```

eps: [0, 0, 1, 1, 1, 1, 0, 0, 1, 0, 1, 0, 0, 0, 0, 1, 0, 0, 1, 1, 0, 1, 1, 0, 1,
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0, 0, 0, 1, 0, 1, 0, 0, 1, 1, 1, 0, 1, 0, 1]

```


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1.2.4 Assinatura de Mensagens

Função para assinatura de uma mensagem com base na chave privada do emissor.

```

[ ]: def ML_DSA_Sign(sk, M, Tq, q, d, n, l, k, tau, gamma_1, gamma_2, omega, beta):

    rho, K, tr, s1, s2, t0 = sk_decode(sk, d, n, l, k)
    print('M:', M)
    print('rho:', rho)
    print('K:', K)
    print('tr:', tr)
    print('s1:', s1)
    print('s2:', s2)
    print('t0:', t0)

    mu = H1024(bytearray(tr+M))[:512]
    print('mu:', mu)

    s1_hat = [ntt(poly, q) for poly in s1]
    s2_hat = [ntt(poly, q) for poly in s2]
    t0_hat = [ntt(poly, q) for poly in t0]
    A_hat = expand_a(rho, q, k, l)
    rnd = [randint(0, 1) for _ in range(256)]
    rho_prime = H1024(bytearray(K + rnd + mu))[:512]
    kappa = 0
    z, zz, h = None, None, None
    while z is None or h is None:
        y = expand_mask(rho_prime, kappa, l, gamma_1)
        NTT_y = []
        for i in range(l):
            y_poly = PolynomialRing(Zmod(q), 'x')(y[i])
            NTT_y.append(ntt(y_poly, q))
        A_NTT = matrix_mntl(A_hat, NTT_y, q)
        w = [ntt_inverse(PolynomialRing(Zmod(q), 'x')(A_NTT_row), q) for
        ↪ A_NTT_row in A_NTT]
        w1 = [[high_bits(n, q, gamma_2) for n in poly] for poly in w]
        c_til = H1024(bytearray(mu + w1_encode(w1, k, q, gamma_2)))[: (2*Tq)]
        c_til_1, c_til_2 = c_til[:256], c_til[256:]

        c = sample_in_ball(c_til_1, tau)
        print('c:', c)

        c_poly = PolynomialRing(Zmod(q), 'x')(c)
        c_hat = ntt(c_poly, q)
        cs1_hat = [ntt_inverse(PolynomialRing(Zmod(q),
        ↪ 'x')(polynomial_mul(c_hat, s_hat, q)), q) for s_hat in s1_hat]
        cs2_hat = [ntt_inverse(PolynomialRing(Zmod(q),
        ↪ 'x')(polynomial_mul(c_hat, s_hat, q)), q) for s_hat in s2_hat]
        z = [[Integer(y[i][j]) + Integer(cs1_hat[i][j]) for j in
        ↪ range(len(cs1_hat[i]))] for i in range(len(cs1_hat))]

```

```

        r0 = [[low_bits(Integer(w[i][j]) - Integer(cs2_hat[i][j])), q, gamma_2)
↪for j in range(len(cs2_hat[i]))] for i in range(len(cs2_hat))]
        zz = [[mod_plus_minus(ze,q) for ze in z1] for z1 in z]

        if max(map(max, zz)) >= gamma_1 - beta or max(map(max, r0)) >= gamma_2
↪- beta:
            z, h = None, None
        else:
            ct0_hat = [ntt_inverse(PolynomialRing(Zmod(q),
↪'x')(polynomial_mul(c_hat,t_hat,q)), q) for t_hat in t0_hat]
            h = [[make_hint((Integer(-1) *
↪Integer(ct0_hat[x][y])), (Integer(w[x][y]) - Integer(cs2_hat[x][y]) + Integer(ct0_hat[x][y])), q,
↪for y in range(len(w[x]))] for x in range(len(w))]
            ct0_pm = [[mod_plus_minus(y,q) for y in x] for x in ct0_hat]
            if max(map(max, ct0_pm)) >= gamma_2 or sum(map(sum, h)) > omega:
                z, h = None, None
            kappa += 1
        sigma = sig_encode(c_til, zz, h, l, gamma_1, omega, k)

    ctilt,z_tilt,ht = sig_decode(sigma, gamma_1, Tq, l, k, omega)
    print('ctilt:',ctilt)
    print('ctil:',c_til)
    print('ctil==ctilt:',c_til==ctilt)
    print('zt:',zt)
    print('z:',zz)
    print('z==zt:',zz==zt)
    print('ht:',ht)
    print('h:',h)
    print('h==ht:',h==ht)

    return sigma

```

```

[ ]: M = "This is a test message."
M_bytes = bytearray(M.encode())
M_bits = bytes_to_bits(M_bytes)

sign = ML_DSA_Sign(sk, M_bits, Tq, q, d, n, l, k, tau, gamma_1, gamma_2, omega,
↪beta)
print('sign:',sign)
print('sign_expected_len:',(Tq // 4)+32*1*(1+bitlen(gamma_1-1))+k+omega)
print('sign_len:',len(sign))

```

```

M: [0, 0, 1, 0, 1, 0, 1, 0, 0, 0, 0, 1, 0, 1, 1, 0, 1, 0, 0, 1, 0, 1, 1, 0, 1,
1, 0, 0, 1, 1, 1, 0, 0, 0, 0, 0, 0, 1, 0, 0, 1, 0, 0, 1, 0, 1, 1, 0, 1, 1, 0, 0,
1, 1, 1, 0, 0, 0, 0, 0, 0, 1, 0, 0, 1, 0, 0, 0, 0, 1, 1, 0, 0, 0, 0, 0, 0, 1, 0,
0, 0, 0, 1, 0, 1, 1, 1, 0, 1, 0, 1, 0, 0, 1, 1, 0, 1, 1, 0, 0, 1, 1, 1, 0, 0, 0,

```

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 1, 1, 0, 1, 1, 0, 0, 1, 1, 1, 0, 1, 1, 0, 0, 1, 1, 1, 0, 1, 0, 0, 0, 0, 1, 1, 0,
 1, 1, 1, 0, 0, 1, 1, 0, 1, 0, 1, 0, 0, 1, 1, 0, 0, 1, 1, 1, 0, 1, 0, 0]
 rho: [1, 1, 1, 1, 0, 0, 1, 1, 0, 0, 0, 1, 1, 0, 1, 0, 1, 0, 1, 1, 0, 1, 1,
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 0, 0, 1, 0, 0, 1, 1, 0, 0, 1, 1, 0, 1, 1, 1]
 K: [1, 1, 0, 0, 0, 1, 0, 1, 0, 1, 1, 0, 1, 0, 0, 1, 0, 1, 0, 0, 1, 1, 0, 0, 1,
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 tr: [0, 1, 1, 1, 0, 1, 1, 1, 1, 0, 1, 1, 1, 0, 1, 0, 0, 1, 1, 0, 1, 1, 0, 0, 1,
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sign_expected_len: 2420
sign_len: 2420

```

1.2.5 Verificação da Assinatura

Função para verificação da assinatura com base na chave pública do emissor e da mensagem em questão.

```

[ ]: def ML_DSA_Verify(pk, M, sigma, q, tau, gamma_1, gamma_2, omega, beta, Tq, k, l, d):
    rho, t1 = pk_decode(pk, q, d, k)
    print('rho:', rho)
    print('t1:', t1)

    c_til, z, h = sig_decode(sigma, gamma_1, Tq, l, k, omega)
    ctil_, _ = c_til[:256], c_til[256:]
    print('c_til:', c_til)
    print('z:', z)
    print('h:', h)

    if h is None:
        return False

    A_hat = expand_a(rho, q, k, l)

```

```

print('A_hat:',A_hat)

tr = H1024(bytearray(pk)[:512])
print('tr:',tr)

mu = H1024(bytearray(tr + M)[:512])
print('mu:',mu)

c = sample_in_ball(ctil_, tau)
print('c:',c)

ntt_z = [ntt(PolynomialRing(Zmod(q), 'x')(poly), q) for poly in z]
A_NTT = matrix_mul(A_hat, ntt_z, q)
ntt_c = ntt(PolynomialRing(Zmod(q), 'x')(c), q)
ntt_t1= [ntt(PolynomialRing(Zmod(q), 'x')([x*(2**d) for x in poly])), q) for
poly in t1]
t1_c = [polynomial_mul(ntt_t1[i], ntt_c, q) for i in range(len(t1))]
fntt=[[Integer(A_NTT[i][j])-Integer(t1_c[i][j]))% q for j in
range(len(A_NTT[i]))] for i in range(len(A_NTT))]
waprox = [ntt_inverse(PolynomialRing(Zmod(q), 'x')(poly), q) for poly in
fntt]
w_prime = [[use_hint(Integer(h[i][j]) % q,Integer(waprox[i][j]),q,gamma_2)
for j in range(len(waprox[i]))] for i in range(len(waprox))]
c_til_ = H1024(bytearray(mu + w1_encode(w_prime, k, q, gamma_2))[:2*Tq])
zz = [[mod_plus_minus(ze,q) for ze in z1] for z1 in z]
return c_til==c_til_ and max(map(max, zz)) < gamma_1 - beta and
sum(map(sum, h)) <= omega

```

```

[ ]: is_valid = ML_DSA_Verify(pk, M_bits, sign, q, tau, gamma_1, gamma_2, omega,
beta, Tq, k, l, d)

if is_valid:
    print("Signature is valid.")
else:
    print("Signature is invalid.")

```

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```

Signature is valid.

1.2.6 Testes

Estes testes foram realizados com o intuito de verificar a corretude do código desenvolvido para os diferentes níveis de segurança. Para assegurar o bom funcionamento interno do código estes testes apresentam todas as variáveis relevantes.

Para testes dedicados apenas à execução do código e a sua performance deve referir ao exercício 3.

```

[ ]: def Dilitium_Test(version, message):
    q = 8380417
    d = 13
    tau=39
    lbd = 128
    gamma_1 = 2**17
    gamma_2 = (q - 1) // 88
    k = 4
    l = 4
    n = 2
    beta = 78

```

```

omega = 80
if version == 65:
    tau=49
    lbd = 192
    gamma_1 = 2**19
    gamma_2 = (q - 1) // 32
    k = 6
    l = 5
    n = 4
    beta = 196
    omega = 55
elif version == 87:
    tau=60
    lbd = 256
    gamma_1 = 2**19
    gamma_2 = (q - 1) // 32
    k = 8
    l = 7
    n = 2
    beta = 120
    omega = 75

pk, sk = ML_DSA_KeyGen(k, l, q, d, n)
print('pk:',pk)
print('sk:',sk)

M_bytes = bytearray(message.encode())
M_bits = bytes_to_bits(M_bytes)

sign = ML_DSA_Sign(sk, M_bits, lbd, q, d, n, l, k, tau, gamma_1, gamma_2,
↪omega, beta)
print('sign:',sign)
print('sign_expected_len:',(lbd//4)+32*l*(1+bitlen(gamma_1-1))+k+omega)
print('sign_len:',len(sign))

is_valid = ML_DSA_Verify(pk, M_bits, sign, q, tau, gamma_1, gamma_2, omega,
↪beta, lbd, k, l, d)

if is_valid:
    print("Signature is valid.")
    return True
else:
    print("Signature is invalid.")
    return False

```

```

[ ]: message = input("Enter the message: ")
for version in [44, 65, 87]:

```

```

print("Version", version)
start_time = time.time()
Dilitium_Test(version,message)
print("Execution time with MLS-DSA-%d: %s seconds", version, time.time() -
↪start_time)

```

Version 44

eps: [0, 1, 1, 1, 1, 1, 1, 0, 0, 0, 0, 0, 1, 0, 0, 1, 1, 1, 0, 0, 0, 0, 0, 1, 1,
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Signature is valid.

Execution time with MLS-DSA-%d: %s seconds 44 5.084598779678345

Version 65

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1]

c: [0, 0, 0, 0, -1, 0, -1, 0, 0, 1, 0, 0, 0, 0, 0, -1, 1, 0, 0, 1, 0, 0, 0, 0,
0, 0, 0, 0, 0, -1, 0, 0, 0, 0, 0, -1, 0, 0, -1, -1, 0, 1, 0, 0, 0, 0, 1, 0, 0,
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0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, -1, 0, 0, 0, -1, 0, 0, 0, -1, 0, 0, 0, 0, -1,
0]

Signature is valid.

Execution time with MLS-DSA-%d: %s seconds 87 15.64228105545044

1.3 Discussão

Este capítulo dedica-se a defender a implementação apresentada neste notebook contra a indicada no documento de especificação fornecido. Esta necessidade surge dos erros de especificação presentes no documento bem como diversas incongruências que levam a inconsistências entre os resultados obtidos pela implementação e os resultados esperados.

Abaixo apresentamos a tabela de tamanhos, em bytes, disponível no documento de especificação:

i1

De seguida apresentamos a tabela de tamanhos obtida pela implementação:

	Private Key	Secret Key	Signature
ML-DSA-44	2560	1312	2420
ML-DSA-65	4032	1952	3309
ML-DSA-87	4896	2592	4627

Como podemos observar, os valores das duas tabelas apresentam diferenças significativas. Iniciando pelo tamanho da chave privada, o documento de especificação indica que a chave privada tem 2528 bytes para ML-DSA-44. Olhemos assim para os parâmetros de ML-DSA-44:

i2

Bem como a especificação do tamanho da chave privada:

i3

Com base nisto podemos calcular o tamanho esperado para a mesma:

$$32+32+64+32((1+k)*bitlen(2n)+dk)$$

Substituindo agora pelos parâmetros de ML-DSA-44:

$$\begin{aligned} &32+32+64+32((4+4)*bitlen(2*2)+(13*4)) = \\ &128+32(8*3+52) = \\ &128+32(24+52) = \\ &128+32(76) = \\ &128+2432 = \\ &2560 \end{aligned}$$

O que corresponde ao valor obtido pela implementação mas não ao valor indicado no documento de especificação. Este erro é também observado para os restantes tamanhos de chave.

O problema aumenta quando olhamos para o tamanho da assinatura onde as inconsistências são ainda maiores. Podemos observar que o tamanho obtido para a assinatura em ML-DSA-44 é congruente com o esperado, no entanto, para os restantes tamanhos de chave, os valores obtidos apresentam variações significativas.

Isto ocorre pois a proposta é baseada em valores “hard coded”, relevando problemas sérios com a proposta. Vejamos a especificação da assinatura:

i4

Onde podemos observar que o tamanho da assinatura é calculado da seguinte forma:

$32 + l * 32 * (1 + \text{bitlen}(y1 - 1)) + w + k$

Observemos agora a especificação da função responsável por calcular a assinatura:

i5

Observamos de imediato que o cálculo do tamanho da assinatura é feito de forma diferente, tendo agora em conta o valor de λ . Relembrando os parametros dos diferentes ML-DSA, sabemos que o valor de λ aumenta e, como tal, $\lambda/4$ é, respetivamente, [32,48,64]. Assim, o tamanho da assinatura difere uma vez que o valor apresentado foi calculado de forma errada e não tem em conta o valor de λ .

Assim sendo, contrariamente ao apresentado no papel de especificação, a implementação apresentada neste notebook é a correta e a que deve ser seguida.

Estes são apenas os exemplos relevantes para a avaliação dos resultados obtidos. Deve no entanto ser referido que o papel apresenta muitas mais inconsistências e erros que não foram abordados nesta descrição por não serem tão relevantes. Estes incluem, mas não se limitam a, inconsistências na definição de variáveis, incongruências na especificação e chamada de funções ou até falta de informação relevante.