基于参数优化批处理的 TLS 协议*

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Parameter Optimization-Based Batching TLS Protocol

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Abstract: The primary goal of the Transport Layer Security (TLS) protocol is to provide confidentiality and data integrity between two communicating entities. Since the most computationally expensive step in the TLS handshake protocol is the server's RSA decryption, it is introduced that optimal batch RSA can be used to speedup TLS session initialization. This paper first indicates that the previous batch method is impractical since it requires a multiple of certificates, then it proposes the unique certificate scheme to overcome the problem. It is also introduced that the batching parameter is optimized when integrating users' requirements for Internet Quality of Service (QoS). To select the optimal batching parameters, not only the server's performance but also the client's tolerable waiting time is considered. Based on the analysis of the mean queue time, batching service time and the stability of the system, a novel batch optimal scheduling algorithm which is deployed in a batching Web server is proposed. Finally, the proposed algorithm is evaluated to be practical and efficient through both analysis and simulation studies.

Key words: transport layer security; batch RSA; TLS handshake; mean response time; tolerable waiting time

摘 要: TLS(transport layer security)协议的基本设计目标是为两个通信实体之间提供数据的保密性和完整性.由于在传输层安全握手协议中最耗费计算资源的步骤是服务器 RSA 解密运算,优化的批处理的 RSA 方法提出可以用于加速 TLS 会话的初始化.首先指出了以前的批处理方法由于要求多证书实现而实用性不强.然后提出了单一证书策略的方法,从而克服了这一问题.还提出结合用户对于因特网服务质量的要求优化了批处理参数.为了选择优化的

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批处理的参数,不仅考虑了服务器的性能,而且还考虑了客户可容忍的等待时间.通过分析并在阐述平均排队时间、批处理服务时间和系统稳定性的基础上提出了一种新颖的优化批处理调度算法,已部署在服务器上.最后通过分析和模拟两种方法验证了所提出方案的实用性和有效性.

关键词: 传输层安全协议;批处理 RSA;TLS 握手协议;平均响应时间;可容忍的等待时间
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1 Introduction

Secure communications such as Internet banking and e-commerce are an intrinsic demand of today's world of online transactions. TLS protects communications by encrypting messages with a secret key negotiated in the TLS handshake protocol. Such a protocol allows the server and the client to authenticate each other and to negotiate an encryption algorithm and cryptographic keys before transmitting and receiving the first byte of data[1]. However, such a protocol needs intensive computational resource due to the cost of public-key operations.

The proposed scheme in this paper focuses on the batching technology which is a software-only approach for speeding up TLS's performance on a web server. Starting-point of the proposed scheme is a technique due to Fiat[2] for batch RSA decryption. Shacham and Boneh proved that it is impossible to use a single certificate in the present TLS system[3]. Whereas, this paper adapts the certificate mechanism so as to provide TLS setup with unique certificate issued by Certificate Authority (CA). Batch size is equal to four in the scheme of Shacham and Boneh[3]. However, it ignores the satisfaction of the users' requirements for Quality of Service such as tolerable waiting time. Tolerable waiting time is defined as the delay time a client can tolerate between a request for a secure web page and receiving the page. In addition, the proposed scheme in this paper models the client request as an M/D/1 queue[4] and uses approximate analytical solution of mean response time to optimize the batch size of the server. Consequently, the proposed optimal batch scheduling algorithm is employed in a batching web server.

The rest of the paper is organized as follows. Section 2 describes the existing batch method with Batch RSA and describes its problems. The proposed unique certificate scheme in batching TLS is presented in Section 3. The analytical model of parameter optimization in batching TLS handshake is presented in Section 4. Section 5 validates the solutions through both analysis and simulation studies.

2 Preliminaries

Definition 1. Given b distinct and pairwise relatively prime public keys $e_1,...,e_b$ all sharing a common modulus $N=pq$, relatively prime to $\phi(N)=(p-1)(q-1)$. n is the bit length of the public modulus N and k the bit length of the bigger of e_i. Given plaintext messages $m_1,...,m_b$. Furthermore, we have b encrypted messages $v_1,...,v_b$ (i.e. $v_i = m_i^{e_i} \bmod N$) one encrypted with each key. The multiplication computation phase is to generate the product $v = \prod_{i=1}^{b} v_i^{e/e_i} \bmod N$, where $e = \prod_{i=1}^{b} e_i$. The exponentiation phase yields $v^{1/e} \bmod N = \prod_{i=1}^{b} v_i^{1/e_i} \bmod N$, which is stored as m. The division computation phase is to break up the product m to obtain the plaintexts $m_i = v_i^{1/e_i}$ which we wish to decrypt simultaneously. This procedure is called Batch RSA[2].

Example. Fiat observed that when using small public exponent e_1 and e_2, it is possible to decrypt two cipher texts for approximately the price of one[3]. Suppose v_1 and v_2 is a cipher text obtained by encryption using the public key (N,3) and (N,5). Then the product $m = (v_1^5 \cdot v_2^3)^{1/15} \bmod N$ can be computed according to Definition 1. To decrypt m_1 and m_2, we must compute $v_1^{1/3}$ and $v_2^{1/5}$ mod N as follows:

$$v_1^{1/3} \bmod N = \frac{m^{10}}{v_1^3 \cdot v_2^2},\ v_2^{1/5} \bmod N = \frac{m^6}{v_1^2 \cdot v_2} \tag{1}$$

Shacham and Boneh showed that it is not possible to batch when the same public key is used for more than one message[3]. They provide a multiple certificate to implement the batch method by assigning the different public key in TLS handshake. The method has following disadvantages: Requirement for many different RSA certificates; additional payment for certificates; extra maintenance works of multiple certifications. The proposed unique certificate scheme solves the impractical of multiple certificate method in next section.

3 Unique Certificate Scheme in Batching TLS Handshake

In the standard TLS protocol, each client encrypts a 48-byte pre-master secret using e_i as the encryption exponents, and the server decrypts the cipher text independently so as to get the *Pre-master secret*. But batch RSA obtains the *Pre-master secrets* from multiple clients and hence improves the performance significantly.

Our unique certificate method is to reuse the message *ServerHello.random* in the protocol (see Fig.1). For simplicity, we only show the related processes and the modified information in the standard TLS handshake protocol. The following procedure is the unique certificate scheme for SSL handshake protocol: (1) Clients send "*Client hello*" massage that includes the cipher suits to the server and create random nonce r_c respectively. (2) Server responds with a "server hello" massage that includes server's public-key certificate and a random nonce r_s. In this improvement, e_i is actually a part of *ServerHello.random*. Server only needs to send unique certificate to all the clients. (3) Clients choose a secret random 48-byte *Pre-master secret* m_1 and m_2 by inputting values m_1, m_2, r_c, r_s into hash function $f()$. It then encrypts m_i with e_i which is different from server's public-key and attaches the ciphertext to a "*Client key exchange*" message that is sent to server. (4) Server decrypts the *Pre-master secret* m_1 and m_2 simultaneously using batch RSA, and uses it to compute the *Shared master secret* s_1 and s_2 respectively.

The client will verify the certificate as usual, but encrypt the *pre-master secret* with received e_i instead of the public exponent in the certificate. Therefore, no extra charge is required, and it is easy to manage the certificate. On the other hand, since the certificate is used to prove the owner who knows the factors of the RSA moduli N only, this adaptation does not undermine the security strength of TLS protocol.

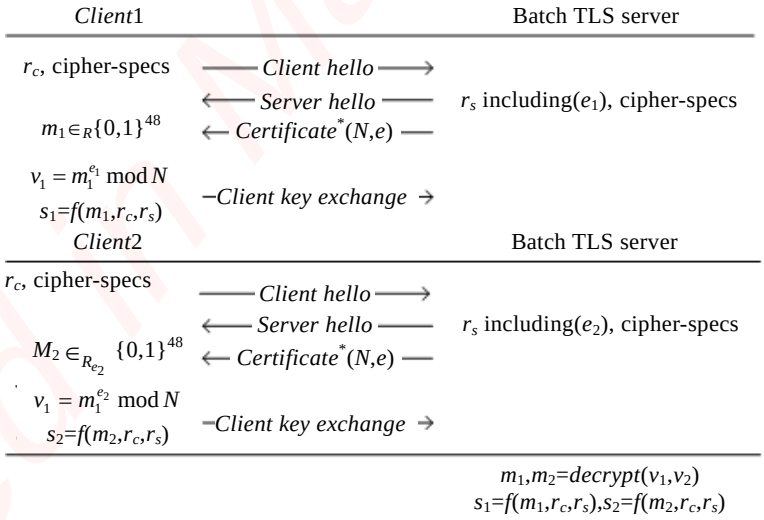


Fig.1 Unique certificate scheme

4 Analytical Model of Parameter Optimization in Batching TLS Handshake

In this section, analytical model of parameter optimization is constructed. The proposed scheme models the client request as an M/D/1 queue and uses approximate solution of mean response time to optimize the batch size of

the server. Consequently, based on the analysis of the stability of the system, the proposed optimal batch scheduling algorithm is employed in a batching Web server.

4.1 Analytical mean queue time in batching queue model M/D/1

Suppose the client arrival process is Poisson distributed with an arrival rate, and the server response is regarded as an M/D/1 queue. Let the batching service time be τ which is determined by the batching size b.

The M/D/1 model can be approximated with a semi-Markov process (see Fig.2). The state of semi-Markov process is described by (i) where i indicates the number of clients waiting in the queue with i=idle and idle indicates the server is idle. Let the mean residual service time be T_r=0.5τ[4].

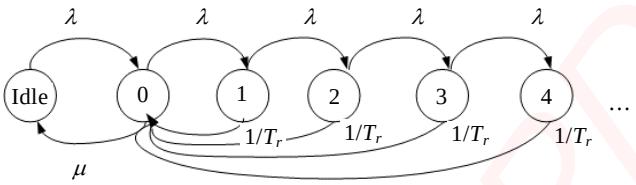


Fig.2 Semi-Markov process model of batching server

Let A_0 be the mean holding time in state idle, A_1 be the mean holding time in state (0), and A_2 be the mean holding time in state (i), for i>0. Thus

$$A_0=\int_0^\infty t\lambda e^{-\lambda t}\mathrm{d}t=1/\lambda,\ A_1=\int_0^\tau t\lambda e^{-\lambda t}\mathrm{d}t+\int_\tau^\infty \lambda \mathrm{e}^{-\lambda t}\mathrm{d}t=\eta_1/\lambda\quad A_2=\int_0^{T_r} t\lambda e^{-\lambda t}\mathrm{d}t+\int_{T_r}^\infty \lambda e^{-\lambda t}\mathrm{d}t=\eta_2/\lambda \tag{2}$$

where, η_1=1–e$^{-\lambda\tau}$ denotes the Markov transition Probability from idle to state (0), and η_2=1–e$^{-0.5\lambda\tau}$ denotes the Markov transition state (i) to state (i+1), for i>0.

Let π_0^* corresponds to the state (0). Then, the steady distribution π_0^* for semi-Markov can be solved as π_0^*=(1–η_1)(1–η_2)/(1+$\eta_1\eta_2$–η_2) due to Ref.[5] (see Fig.2). *Prob*(*idle*) is approximated by π_0^*, which is obtained by solving the semi-Markov processed. Then the mean queue time with batching T_q is solved using the residual service time T_r and the steady state distribution π_0^* for semi-Markov when the server is idle.

$$T_q=(1-Prob(idle))T_r=(1-\pi^*)T_r=(1-(1-\eta_1)(1-\eta_2)/(1+\eta_1\eta_2-\eta_2))T_r \tag{3}$$

4.2 Analytical batching service time

Let the batching RSA decryption time in TLS handshake time be T_b. Let n be the bit length of the public modulus N and k be the bit length of the bigger of exponent. Because the public exponent e_i is chosen as small as possible to make auxiliary exponentiations cheap, the low-cost operations in the computation cost estimation can be ignored.

Asymptotic behavior of analysis of batch RSA can be estimated as $3n^3+(42b+k(3b^3+3b)-1)n^2+o(n^2)$[6].

The classic RSA's decryption mainly includes exponentiation computation which costs $3n^3+n^2+o(n^2)$.

It is assumed that the classic RSA decryption time is computed in advance and denoted as T_{rsa} with 1024 bits public modulus N and the exponent e 65537. The batching RSA decryption time in TLS handshake T_b can be estimated as the following.

As a result, the batching RSA decryption time is

$$T_b=\left(\frac{3n^3+n^2(42b+k(3b^3+3b)-1)}{b(3n^3+n^2)}\right)bT_{rsa}=\left(\frac{3n+42b+k(3b^3+3b)-1}{b(3n+1)}\right)bT_{rsa} \tag{4}$$

Since T_b is the majority of service time, the batching service time of the server τ is T_b roughly. As a TLS server waits for more than one RSA decryption request and performs one big computation for all decryptions, it can save a lot of running time capacity, being able to perform more TLS handshakes.

Theorem 1. To satisfy the client's requirement for the stability of the system, the batching service time is less than the batch size multiplying mean Poisson distributed arrival time interval when the time in the Batch Queue Model M/D/1, thus

$$\tau \approx T_b < b/\lambda \tag{5}$$

Proof: Let X_i(i=1,2,...) be the arrival time interval of two consecutive requests, and Y be the time interval of b consecutive requests. If the system achieves the stability when the time $t \to \infty$ for M/D/1 queue model, $T_b < E(Y)$, where $E(Y)$ is the expected value of Y. Because the X_i is a random variable with independent identical distribution, the average arrival time interval of b consecutive requests is

$$E(Y) = E\left(\sum_{i=1}^{b} X_i\right) = bE(X_i) = b/\lambda \tag{6}$$

Then Theorem 1 is proved.

Lemma 1. In the Batch Queue Model M/D/1, to satisfy the client's requirement for the stability of the system, thus

$$T_q < b/2\lambda \tag{7}$$

Proof: In the Batch Queue Model M/D/1, the value of T_q is derived following Eq.(3)

$$T_q = \left(1 - \frac{(1-\eta_1)(1-\eta_2)}{(1+\eta_1\eta_2-\eta_2)}\right)T_r = \left(\frac{1-e^{-\lambda\tau}}{1-e^{-\lambda\tau}+e^{-1.5\lambda\tau}}\right)T_r = \left(\frac{e^{-\lambda\tau}-1}{e^{-\lambda\tau}-1+e^{-0.5\lambda\tau}}\right)T_r = \left(\frac{1}{1+\frac{1}{(e^{-\lambda\tau}-1)e^{0.5\lambda\tau}}}\right)T_r \tag{8}$$

where, T_r=0.5τ. Due to Theorem 1, it can be easily described as

$$T_q = \left(\frac{0.5\tau}{1+\frac{1}{(e^{-\lambda\tau}-1)e^{0.5\lambda\tau}}}\right) < \left(\frac{1}{1+\frac{1}{(e^{b}-1)e^{0.5b}}}\right)\left(\frac{b}{2\lambda}\right) \tag{9}$$

It can be easily described as when $b \geq 2$, $0.944 \approx 1+\frac{1}{(e^2-1)e^{0.5\times 2}} \leq 1+\frac{1}{(e^b-1)e^{0.5b}} < 1$. Then the value bound of the upper limit of T_q is estimated as [0.944b/2λ, b/2λ]. Then Lemma 1 is proved.

4.3 Optimal batch scheduling algorithm

If the constants and practical value of the client's tolerable waiting time T_t are known, the upper limit of batch size b can be estimated according to different arrival rates of the client. It is usually expected that the ideal response time of web sites is 1 or 2 seconds[7] and 50% people apparently will wait only 8 seconds for a website to download before they get fed up and move on[7]. It is assumed that the value T_t is equal to 1 second, 2 seconds and 8 seconds as examples both in the analytical model and simulation. The total customer response time T is denoted as the sum of T_q, T_c and T_b, where T_c is the time for waiting other client in the same batching. It is easily derived that the max value of T_c is (b–1)λ. Otherwise, the upper limit of T_b has been estimated as b/λ in Theorem 1. We can also estimate the upper limit of T_q as b/2λ derived from Lemma 1. It is assumed that T will not exceed T_t. The upper limit of b is derived as the following

$$T = T_q + T_c + T_b = \frac{b}{2\lambda} + \frac{(b-1)}{\lambda} + \frac{b}{\lambda} < T_t \Rightarrow b < 0.4(\lambda T_t + 1) \tag{10}$$

The pseudo code (see Fig.3.) shows the optimal batch scheduling algorithm which is employed in a batching web server. Step one sorts b to satisfy max solution of $T_b < b/\lambda$ in ascending order from two to the upper limit using Eq.(10). The computation of T_b is performed using Eq.(5). In step two, the batch server performs a set of related tasks to optimal schedule. The server firstly constructs b queues ($Q(e_1)$,$Q(e_2)$,….,$Q(e_b)$) for every exponent e_i. A

heavily loaded web server using a round strategy when dispatching the exponent to clients would incur minimal latency before receiving b TLS handshake requests. When new requests arrive, the server adds the client to the corresponding queue and initializes a timer for the client. If every queue has client, it means that the condition of optimal batch is satisfied. Then, the server excuses *batch_decryption*(). The meaning of function *batch_decyption* () is to do batch decryption with the client in the head of every not empty queue in the ($Q(e_1)$,$Q(e_2)$,…,$Q(e_b)$). If the condition of optimal batch can not be satisfied, the server waits for a period of time that is equal to T_t surplus the max value of timer of the client in the head of every queue. Then the server does the *batch_decryption*(). The batch server has the ability to fall back on *conventional_RSA_decryption*() when only one client is in queues. If all queues do not have clients, the algorithm terminates.

Step1: Find out the solution of b
Input: T_t, λ;
Output: T_b, optimal batch size.
Begin
1. **Compute** the max batch size. max*batchsize*= *int*(0.4(λT_t+1)) (refer to Eq.(10)).
2. **If** (max*batchsize*<=1) **then** do
3. **conventional_RSA_decryption**(); return;
4. **For** (*b*=2;*b*<=max*batchsize*;*b*++)
5. {Success=false;
6. **Compute** T_b (refer to Eq.(4));
7. **If** (T_b<b/λ) **then** {*Optimalbatchsize*=b; Success=true;}}
8. **If** (!success) **then** return;
9. **If** (success) **then** goto step2();

End

Step2: Optimal batch scheduling
Input: Optimal batch size, T_t;
Output: optimal batch scheduling.
Begin:
1. **Construct** b queues ($Q(e_1)$,$Q(e_2)$,...,$Q(e_b)$) for every exponent e_i. max*timer*=0;
2. **Assign** the exponents {e_1,e_2,…,e_b} to different clients using round robin strategy in *serverhello* message (refer to Fig.1.)
3. **while** ($Q(e_1)$!=Null **or** (e_2)!=Null ... **or** (e_b)!=Null){
4. **If** Client arrived **then** {**match** client. *exponent*=e_i, **enqueue** ($Q(e_i)$,client); **initialize** Client.timer}
5. **If** ($Q(e_1)$!=Null **and** $Q(e_2)$!=Null ... **and** $Q(e_b)$!=Null)
6. **then** {Do **batch_decryption**(); **reset** server_waiting_time; **update** queues ($Q(e_1)$,$Q(e_2)$,...,$Q(e_b)$;)
7. **Else** { **for** (j=1; j<=b; j++)
8. {**If** (($Q(e_j)$!=Null) **and** ($Q(e_j)$.*head*.*timer*>=max*timer*))
9. {max*timer*=($Q(e_j)$.*head*.*timer*); } }
10. **If** (server waiting time>=T_t–max*timer*) **then**
11. {do **batch_decryption**(); **reset** server_waiting_time; **update** queues ($Q(e_1)$,$Q(e_2)$,...,$Q(e_b)$;)
12. **Else** continuing waiting for request of client;}

End

Fig.3 Optimal batch scheduling algorithm

5 Validation of Analytical Models and Performance Evaluation Study

5.1 Experiment configuration

The analytical models are executed on a machine with a Dell Intel Pentium IV processor clocked at 3.20GHz and 1GMB RAM. Specifically, this paper performs the simulation of batching RSA with very small public exponents, namely e=3,5,7,11,13,17 etc. The simulation result of the conventional RSA decryption time T_{rsa} with larger public exponent, namely e=65537 is about 32 ms which is tested using reiterative results. It is assumed public modulus N is 1024 bits length.

5.2 Validation of analytical models

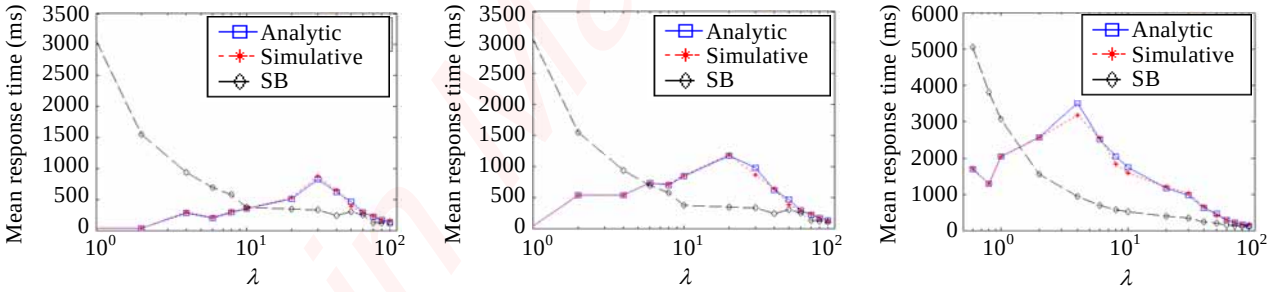
Table 1 validates optimal batch size described by the analytical model. As small arrival rates, b is almost uniform calculated by our analytical model (Table 1). Since the arrival rates are small (i.e., T_t=8, λ<0.6), there is very little opportunity to batch, and therefore, the solution of b is relative small (Table 1). Even at higher arrival rate, the analytical result and simulation result are very close. The solution of the optimal batch size is increased with λ both in analytic and simulation when λ<30 (i.e., T_t=1) approximately. Otherwise, T in this case is not increased obviously. The solution of b is decreased with the λ when λ>30 approximately.

Table 1 Optimal batch size results validation

λ	Optimal batch size					
	Analytical model			Simulation results		
	T_t=1	T_t=2	T_t=8	T_t=1	T_t=2	T_t=8
0.6	–	–	2	–	–	2
1	–	–	3	–	–	3
2	–	2	6	–	2	6
3	–	2	10	–	2	10
4	2	3	13	2	3	12
5	2	4	13	2	4	12
10	4	8	13	4	8	13
20	8	13	13	8	12	13
30	12	12	12	12	12	12
40	11	11	11	10	11	11
50	10	10	10	10	9	10
60	8	8	8	8	8	8
80	6	7	6	6	6	6
90	5	5	5	6	5	6
100	5	5	5	6	4	6

5.3 Performance evaluation

Fig.4(a)~Fig.4(c) illustrates the analytical mean response time T, our simulation results and that of SB (Shacham and Boneh) scheme. When λ is equal to 30 approximately, T reaches Maximum whereas the value is less than 1 second and decreased with the λ when using optimal batch size b (see Fig.4(a)). In the SB scheme, T of a batching system behaves poorly especially when λ does not exceed 10 requests/sec (see Fig.4(a)). When λ is larger than 10 and less than 100 approximately, the performance of the novel scheme and SB scheme are all satisfied with the clients' requirement of tolerable waiting time. However, it is shown that the solutions of b (Table 1) are larger than four. That means the optimal scheme can submit more decryption requests once to decryption device than SB scheme. The other two cases with T_t=2 (see Fig.4(b)) and T_t=8 (see Fig.4(c)) can be analyzed similarly as that with T_t=1 (see Fig.4(a)). The analytical and simulation results of T shows the novel batch scheme behaves nicely.



(a) T_t=1 (b) T_t=2 (c) T_t=8

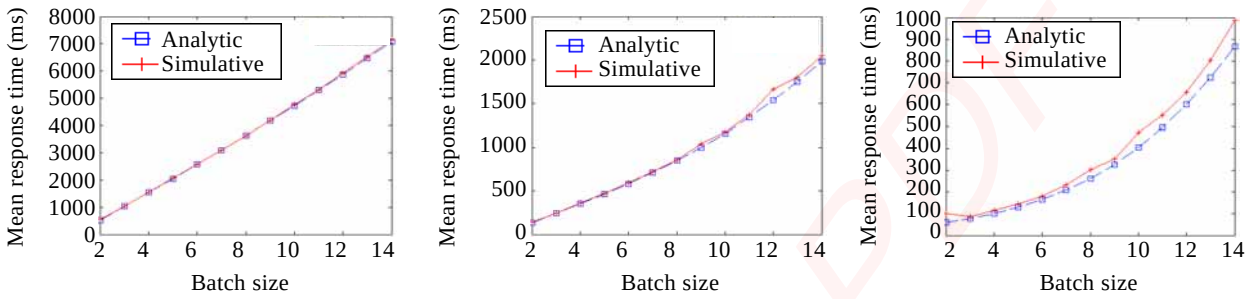
Fig.4 Mean response time validation over client's tolerable waiting time

It is assumed that T_t is equal to 8 seconds in Fig.5(a)~Fig.5(c). These figures show that T is almost linear when λ is relatively small. This is due to the fact that $T=T_q+T_c+T_b$. When λ is relatively small, the main contribution to T is made by T_c. It is evident that the time T_c is increased linearly with b. T_b is also increased with b. Therefore T is also increased with b when λ is relatively large (i. e., λ=80).

A non-batching system becomes unstable when $\lambda>1/T_{rsa}=1/0.032=31.25$ due to the fact that a non-batching system becomes unstable when $\lambda>\tau$. But with batching, a batch system behaves nicely even at high loads. When the non-batching system is stable, the mean response time T' can be estimated as Eq.(11) (see Fig.6).The mean service time τ' is deterministic in the non-batching in M/D/1 queue model. Since T_{rsa} is the majority of service time, the mean service time τ' of the server is roughly T_{rsa}[5].

$$T' = \tau' + \tau'\left(\frac{\tau'\lambda}{2(1-\tau'\lambda)}\right) \approx T_{rsa} + T_{rsa}\left(\frac{T_{rsa}\lambda}{2(1-T_{rsa}\lambda)}\right) \tag{11}$$

Figure 7 (i.e. T_t=8) illustrates the comparison of the mean response time of the batching schemes with the non-batching scheme. The vertical axis in each graph is the mean response time over batch size divided by the mean response time with non-batching scheme. Refering to Table.1, it is shown that the optimal batch size is equal to 12 when λ=30. The speedup of mean response time is an optimal one which equals to 5.23 approximately. It is clear that with the optimal batch size the batching system has considerable advantages whereas costs little.



(a) λ=2 (b) λ=10 (c) λ=80

Fig.5 Mean response time validation over batch size

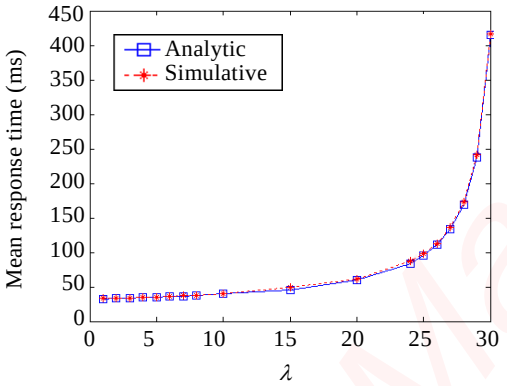


Fig.6 Mean response time for non-batching scheme

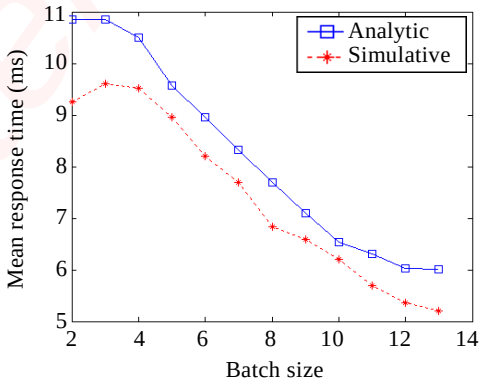


Fig.7 Mean response time speedup against non-batching

6 Conclusions

In conclusion, this paper proposes a novel method of assigning the set of public exponent e_i only using unique certificate in batching TLS handshake protocol. This paper also optimizes the batch size by developing an analytical model which satisfies the stability conditions of the system for the batching TLS handshake. The novel optimal batch scheduling algorithm is employed in a batching web server which satisfies the clients' requirement of stability of system and tolerable waiting time. The parameter optimization-based batching TLS handshake is a viable option for secure communications.

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24. 基于双 PowerPC 7447A 处理器的嵌入式系统硬件设计
25. 基于 PowerPC603e 通用处理模块的设计与实现
26. 嵌入式微机 MPC555 驻留片内监控器的开发与实现
27. 基于 PowerPC 和 DSP 的电能质量在线监测装置的研制
28. 基于 PowerPC 架构多核处理器嵌入式系统硬件设计
29. 基于 PowerPC 的多屏系统设计
30. 基于 PowerPC 的嵌入式 SMP 系统设计
31. 基于 MPC850 的多功能通信管理器
32. 基于 MPC8640D 处理系统的技术研究
33. 基于双核 MPC8641D 处理器的计算机模块设计
34. 基于 MPC8641D 处理器的对称多处理技术研究

ARM：

1. 基于 DiskOnChip 2000 的驱动程序设计及应用
2. 基于 ARM 体系的 PC-104 总线设计
3. 基于 ARM 的嵌入式系统中断处理机制研究
4. 设计 ARM 的中断处理
5. 基于 ARM 的数据采集系统并行总线的驱动设计
6. S3C2410 下的 TFT LCD 驱动源码
7. STM32 SD 卡移植 FATFS 文件系统源码
8. STM32 ADC 多通道源码

9. ARM Linux 在 EP7312 上的移植
10. ARM 经典 300 问
11. 基于 S5PV210 的频谱监测设备嵌入式系统设计与实现
12. Uboot 中 start.S 源码的指令级的详尽解析
13. 基于 ARM9 的嵌入式 Zigbee 网关设计与实现
14. 基于 S3C6410 处理器的嵌入式 Linux 系统移植
15. CortexA8 平台的μC-OSⅡ及 LwIP 协议栈的移植与实现
16. 基于 ARM 的嵌入式 Linux 无线网卡设备驱动设计
17. ARM S3C2440 Linux ADC 驱动
18. ARM S3C2440 Linux 触摸屏驱动
19. Linux 和 Cortex-A8 的视频处理及数字微波传输系统设计
20. Nand Flash 启动模式下的 Uboot 移植
21. 基于 ARM 处理器的 UART 设计
22. ARM CortexM3 处理器故障的分析与处理
23. ARM 微处理器启动和调试浅析
24. 基于 ARM 系统下映像文件的执行与中断运行机制的实现
25. 中断调用方式的 ARM 二次开发接口设计
26. ARM11 嵌入式系统 Linux 下 LCD 的驱动设计
27. Uboot 在 S3C2440 上的移植
28. 基于 ARM11 的嵌入式无线视频终端的设计
29. 基于 S3C6410 的 Uboot 分析与移植
30. 基于 ARM 嵌入式系统的高保真无损音乐播放器设计
31. UBoot 在 Mini6410 上的移植
32. 基于 ARM11 的嵌入式 Linux NAND FLASH 模拟 U 盘挂载分析与实现
33. 基于 ARM11 的电源完整性分析
34. 基于 ARM S3C6410 的 uboot 分析与移植
35. 基于 S5PC100 移动视频监控终端的设计与实现
36. UBoot 在 AT91RM9200 上的移植简析
37. 基于工控级 AT91RM9200 开发板的 UBoot 移植分析

Hardware：

1. DSP 电源的典型设计
2. 高频脉冲电源设计
3. 电源的综合保护设计
4. 任意波形电源的设计
5. 高速 PCB 信号完整性分析及应用
6. DM642 高速图像采集系统的电磁干扰设计
7. 使用 COMExpress Nano 工控板实现 IP 调度设备

8. 基于 COM Express 架构的数据记录仪的设计与实现
9. 基于 COM Express 的信号系统逻辑运算单元设计
10. 基于 COM Express 的回波预处理模块设计
11. 基于 X86 平台的简单多任务内核的分析与实现
12. 基于 UEFI Shell 的 PreOS Application 的开发与研究
13. 基于 UEFI 固件的恶意代码防范技术研究
14. MIPS 架构计算机平台的支持固件研究
15. 基于 UEFI 固件的攻击验证技术研究
16. 基于 UEFI 的 Application 和 Driver 的分析与开发
17. 基于 UEFI 的可信 BIOS 研究与实现
18. 基于 UEFI 的国产计算机平台 BIOS 研究
19. 基于 UEFI 的安全模块设计分析
20. 基于 FPGA NiosⅡ的等精度频率计设计
21. 基于 FPGA 的 SOPC 设计
22. 基于 SOPC 基本信号产生器的设计与实现
23. 基于龙芯平台的 PMON 研究与开发
24. 基于 X86 平台的嵌入式 BIOS 可配置设计
25. 基于龙芯 2F 架构的 PMON 分析与优化
26. CPU 与 GPU 之间接口电路的设计与实现
27. 基于龙芯 1A 平台的 PMON 源码编译和启动分析
28. 基于 PC104 工控机的嵌入式直流监控装置的设计
29. GPGPU 技术研究与发展
30. GPU 实现的高速 FIR 数字滤波算法
31. 一种基于 CPUGPU 异构计算的混合编程模型
32. 面向 OpenCL 模型的 GPU 性能优化
33. 基于 GPU 的 FDTD 算法
34. 基于 GPU 的瑕疵检测
35. 基于 GPU 通用计算的分析与研究
36. 面向 OpenCL 架构的 GPGPU 量化性能模型
37. 基于 OpenCL 的图像积分图算法优化研究
38. 基于 OpenCL 的均值平移算法在多个众核平台的性能优化研究
39. 基于 OpenCL 的异构系统并行编程
40. 嵌入式系统中热备份双机切换技术研究
41. EFI-Tiano 环境下的 AES 算法应用模型
42. EFI 及其安全性研究
43. 基于 UEFI Shell 的 PreOS Application 的开发与研究

Programming:

1. 计算机软件基础数据结构 - 算法
2. 高级数据结构对算法的优化
3. 零基础学算法
4. Linux 环境下基于 TCP 的 Socket 编程浅析
5. Linux 环境下基于 UDP 的 socket 编程浅析
6. 基于 Socket 的网络编程技术及其实现
7. 数据结构考题 - 第 1 章 绪论
8. 数据结构考题 - 第 2 章 线性表
9. 数据结构考题 - 第 2 章 线性表 - 答案
10. 基于小波变换与偏微分方程的图像分解及边缘检测
11. 基于图像能量的布匹瑕疵检测方法
12. 基于 OpenCL 的拉普拉斯图像增强算法优化研究
13. 异构平台上基于 OpenCL 的 FFT 实现与优化
14. 数据结构考题 - 第 4 章 串
15. 数据结构考题 - 第 4 章 串答案
16. 用 IPv6 编程接口实现有连接通信的方法

FPGA / CPLD:

1. 一种基于并行处理器的快速车道线检测系统及 FPGA 实现
2. 基于 FPGA 和 DSP 的 DBF 实现
3. 高速浮点运算单元的 FPGA 实现
4. DLMS 算法的脉动阵结构设计及 FPGA 实现
5. 一种基于 FPGA 的 3DES 加密算法实现
6. 可编程 FIR 滤波器的 FPGA 实现
7. 基于 FPGA 的 AES 加密算法的高速实现
8. 基于 FPGA 的精确时钟同步方法
9. 应用分布式算法在 FPGA 平台实现 FIR 低通滤波器
10. 流水线技术在用 FPGA 实现高速 DSP 运算中的应用
11. 基于 FPGA 的 CAN 总线通信节点设计
12. 基于 FPGA 的高速时钟数据恢复电路的实现
13. 基于 FPGA 的高阶高速 FIR 滤波器设计与实现
14. 基于 FPGA 高效实现 FIR 滤波器的研究
15. FPGA 的 VHDL 设计策略
16. 用 FPGA 实现串口通信的设计
17. GPIB 接口的 FPGA 实现