COMPUTATION OF THE $p$-PART OF THE IDEAL CLASS GROUP OF CERTAIN REAL ABELIAN FIELDS

HIROKI SUMIDA-TAKAHASHI

Abstract. Under Greenberg’s conjecture, we give an efficient method to compute the $p$-part of the ideal class group of certain real abelian fields by using cyclotomic units, Gauss sums and prime numbers. As numerical examples, we compute the $p$-part of the ideal class group of the maximal real subfield of $\mathbb{Q}(\sqrt{-f},\zeta_{p^{n+1}})$ in the range $1 < f < 200$ and $5 \leq p < 100000$. In order to explain our method, we show an example whose ideal class group is not cyclic.

1. Introduction

Let $K$ be a number field and $p$ a prime number. Let $K_\mathcal{P}$ be the cyclotomic $\mathbb{Z}_p$-extension of $K$ and $K_n$ the subfield of $K_\mathcal{P}$ such that $[K_n : K] = p^n$. Further let $A_n$ be the $p$-part of the ideal class group of $K_n$. Greenberg’s conjecture claims that $\sharp A_n$ is bounded as $n \to \infty$ if $K$ is totally real. We have not been able to find any counter-example to the conjecture. On the other hand, it has been verified for certain real abelian fields and some prime numbers by computer calculation (cf. [8, 16]).

In [11, 14], under Greenberg’s conjecture, Kraft-Schoof and Ozaki gave a nice method to compute the $p$-part of the ideal class group of certain real abelian fields by using cyclotomic units. In the computation, we need to know whether a cyclotomic unit $c_n \in K_n$ is a $p^{n+1}$th power or not in $K_n$. As the degree of the minimal polynomial for $c_n$ over $\mathbb{Q}$ gets larger, the computation of the minimal polynomial for $\sqrt[p^{n+1}]{c_n}$ becomes more difficult. In [15, 16], by using Gauss sums and prime numbers, we avoided the difficulty and gave an efficient method to compute the $p$-part of the ideal class number of certain real abelian fields. In this paper, combining them, we give an efficient method to compute the $p$-part of the ideal class group.

Following [15, 16], we give numerical examples of the $p$-part of the ideal class group of the maximal real subfield $K_{f,p}$ of $\mathbb{Q}(\sqrt{-f},\zeta_p)$ in the range $1 < f < 200$ and $5 \leq p < 100000$. The first purpose of this computation is to verify Greenberg’s conjecture for each case. In fact we verify the conjecture in the above range. Therefore we can make use of the method of [11, 14] to compute the structure.
of the $p$-part of the ideal class group. Let $\chi$ be the nontrivial Dirichlet character associated to $\mathbb{Q}(\sqrt{-f})$ and $\omega = \omega_p$ the Teichmüller character. Here we call $(p, \chi \omega^k)$ an exceptional pair if and only if $\chi \omega^k(p) = 1$, $\chi \omega^{1-k}(p) \neq 1$, and one of the following conditions is satisfied: $\nu_p(\chi \omega^k) > 0$, $\nu_p(L_p(1, \chi \omega^k)) > 1$, $\nu_p(L_p(0, \chi \omega^k)) > 1$, or $\lambda_p(\chi \omega^k) > 1$, where $\nu_p(\chi \omega^k)$ is the $\chi \omega^k$-part of the Iwasawa $\nu_p$-invariant, $\nu_p$ is the $p$-adic valuation such that $\nu_p(p) = 1$ and $\lambda_p(\chi \omega^k)$ is the degree of the Iwasawa polynomial for $\chi \omega^k$. The second purpose of the computation is to find exceptional pairs, as many as possible for large prime numbers in order to argue about their expected numbers (cf. [17] pp.158–159). From our data, the actual numbers of exceptional pairs seem to be close to the expected numbers.

Following [1], we compute $A_n$ for $f = 4 \cdot 14606$ and $p = 5$ (i.e., $K = K_{4\cdot14606,5}$):

$$
\begin{cases}
A_0 \simeq \mathbb{Z}/p\mathbb{Z} \oplus \mathbb{Z}/p\mathbb{Z}, \\
A_n \simeq \mathbb{Z}/p^2\mathbb{Z} \oplus \mathbb{Z}/p\mathbb{Z} & \text{for } n \geq 1.
\end{cases}
$$

Since $p$ splits in $\mathbb{Q}(\sqrt{-f})$, we need to modify some conditions in order to apply the criterion of [15]. We explain about the modification and difficulty in the following section.

2. A METHOD OF COMPUTATION OF $A_n$

Let $F$ be an abelian field and $p$ an odd prime number. For simplicity, we assume the following condition:

$$(C1) \quad \text{The exponent of } \text{Gal}(F/Q) \text{ divides } p - 1.$$ 

Let $K = F(\zeta_p)$ and $A_n = A_n(K)$ be the $p$-part of the ideal class group of $K_n = F(\zeta_{p^{n+1}})$. Let $D_n$ be the subgroup of $A_n$ consisting of classes which contain an ideal all of whose prime factors lie above $p$. Set $A'_n = A_n/D_n$. Let $M_n$ be the maximal abelian extension of $K_n$ unramified outside $p$. $L_n$ the maximal unramified abelian extension of $K_n$, and $L'_n$ the maximal unramified abelian extension of $K_n$ in which every prime divisor above $p$ splits completely. Set $X_n = \text{Gal}(L_n/K_n)$ and $X'_n = \text{Gal}(L'_n/K_n)$. By the class field theory, we have $A_n \simeq X_n$ and $A'_n \simeq X'_n$. Set $L_\infty = \bigcup L_n$, $L'_\infty = \bigcup L'_n$, $X_\infty = \text{Gal}(L_\infty/K)$ and $X'_\infty = \text{Gal}(L'_\infty/K_n)$.

Set $\Delta = \text{Gal}(K/Q) \simeq \text{Gal}(K_0/Q)$. Let $\psi$ be a Dirichlet character of $\Delta$ and $e_\psi = \frac{1}{\#\Delta} \sum_{\delta \in \Delta} \psi(\delta) \delta^{-1} \in \mathbb{Z}_p[\Delta]$. For a $\mathbb{Z}_p[\Delta]$-module $A$, we denote $e_\psi A$ by $A^\psi$. Let $\lambda_p(\psi)$, $\mu_p(\psi)$ and $\nu_p(\psi)$ (resp. $\lambda'_p(\psi)$, $\mu'_p(\psi)$ and $\nu'_p(\psi)$) be the Iwasawa invariants associated to $A^\psi_n$ (resp. $A'^\psi_n$), i.e.,

$$
\#A^\psi_n = p^{\lambda_p(\psi)n + \mu_p(\psi)p^n + \nu_p(\psi)} \quad \text{(resp. } \#A'^\psi_n = p^{\lambda'_p(\psi)n + \mu'_p(\psi)p^n + \nu'_p(\psi)})
$$

for all sufficiently large integers $n$. By Ferrero-Washington’s theorem in [3], we have $\mu_p(\psi) = \mu'_p(\psi) = 0$ for all $p$ and $\psi$.

Assume that $\psi$ is even. The Iwasawa polynomial $g_\psi(T) \in \mathbb{Z}_p[T]$ for the $p$-adic $L$-function is defined as follows. Let $L_p(s, \psi)$ be the $p$-adic $L$-function constructed in [12]. Let $f_0$ be the least common multiple of $p$ and $f_\psi$ the conductor of $\psi$. By [9] §6, there uniquely exists $G_\psi(T) \in \mathbb{Z}_p[T]$ satisfying $G_\psi((1 + f_0)^{-s} - 1) = L_p(s, \psi)$ for all $s \in \mathbb{Z}_p$ if $\psi \neq \psi^0$. By [4], it was proved that $p$ does not divide $G_\psi(T)$. Therefore, by the $p$-adic Weierstrass preparation theorem, we can uniquely write $G_\psi(T) = g_\psi(T)u_\psi(T)$, where $g_\psi(T)$ is a distinguished polynomial of $\mathbb{Z}_p[T]$ and $u_\psi(T)$ is an invertible element of $\mathbb{Z}_p[[T]]$. Similarly we can define $g^\psi(T) \in \mathbb{Z}_p[T]$.  

from $G^c_n(T) \in \mathbb{Z}[T]$ satisfying $G^c_n((1 + f_0)^s - 1) = L_p(s, \psi)$. Put $\tilde{\lambda}_p(\psi) = \deg g_\psi(T) = \deg g^c_\psi(T)$.

Let $\gamma \in \Gamma = \text{Gal}(\bigcup \mathbb{Q}(\zeta_{f_n})/\mathbb{Q}(\zeta_{f_0})) \simeq \text{Gal}(K_\infty/K_0)$ be a generator of $\Gamma$ such that $\zeta^\gamma_{f_n} = \zeta^1_{f_n} f_0$ for all $n \geq 0$ and $f_n = f_0 p^n$. As usual, we can identify the complete group ring $\mathbb{Z}_p[\Gamma]$ with the formal power series ring $A = \mathbb{Z}_p[[T]]$ by $\gamma = 1 + T$. By this identification, we can consider a $\mathbb{Z}$-module $A$ over $\Lambda = \mathbb{Z}[[T]]$.

Fact 1. The inclusion $\nu_{m,n} = \omega_{m}/\omega_n$ for $m \geq n \geq 0$. For a finitely generated torsion module $A$, we define the Iwasawa polynomial $\text{char}_A(T)$ to be the characteristic polynomial of the action $T$ on $A \otimes \mathbb{Q}_p$ (cf. [17 §13]). By Mazur-Wiles' theorem in [13], $\text{char}_A(X^{-1} \psi) = g^c_\psi(T)$.

Let $p$ be a prime ideal of $K$ over $p$ and $p_n$ the unique prime ideal of $K_n$ over $p$. Denote by $K_{p_n}$ the completion of $K_n$ at $p_n$, and by $\mathcal{U}_{p_n}$ the group of principal units of $K_{p_n}$. Put $\mathcal{V}_{p_n} = \bigcap_{m \geq n} N_{m,n} \mathcal{U}_{p_n}$, $N_{m,n}$ denoting the norm map from $K_{p_m}$ to $K_{p_n}$. We set

$$\mathcal{U}_n = \prod_{p \mid p} \mathcal{U}_{p_n} \quad \text{and} \quad \mathcal{V}_n = \prod_{p \mid p} \mathcal{V}_{p_n},$$

where $p$ runs over all prime ideals of $K$ over $p$.

Let $E'_n$ be the group of units $\varepsilon$ of $K_n$ satisfying $\varepsilon \equiv 1 \text{ mod } p_n$ for all $p_n | p$. Denote by $C_n$ the subgroup of $K_n^\times$ generated by all the units

$$N_{\mathbb{Q}(\zeta_{f_0})/K_n}(1 - \zeta_{f_n})^u, \quad u \in \mathbb{Z} \text{Gal}(K_n/\mathbb{Q})^0,$$

where $X^0$ is the augmentation ideal of the group ring $X$. Denote, respectively, $\mathcal{E}_n$ and $C_n$ as the closures of the images of $E'_n$ and $C'_n = C_n \cap E'_n$ under the diagonal embedding $d_n : E'_n \to \mathcal{U}_n$.

From now on, we also assume the following condition:

(C2) $\psi(p) \neq 1$.

Set $\psi^* = \psi^{-1} \omega$ and $\omega^*_{n} = T - f_0$. Then we have the following facts (see [5 Theorem 1, 2]):

**Fact 1.**

$$\mathcal{U}_{n}^\psi = \mathcal{V}_n^\psi.$$  

If $\psi^*(p) \neq 1$,

$$\mathcal{U}_n^\psi \simeq A/(\omega_n) \quad \text{and} \quad C_n^\psi \simeq (g_\psi(T), \omega_n)/(\omega_n).$$

If $\psi^*(p) = 1$,

$$\mathcal{U}_n^\psi / \mathbb{T}_n \simeq A/(\omega_n) \quad \text{and} \quad C_n^\psi / \mathbb{T}_n \simeq (g_\psi(T), \omega_n)/(\omega_n),$$

where $\mathbb{T}_n = \text{Tor}_2 \mathbb{Z}_n \mathcal{U}_n^\psi \simeq A/(\omega^*_n, \omega_n)$ and $\bar{g}_\psi(T) = g_\psi(T)/\omega^*_n$.

We also have the following fact on $E'_n$ and $\mathcal{E}_n$, which follows from the Leopoldt conjecture for $(K_n, p)$ (cf. [17 §5.5]):

**Fact 2.** The inclusion $d_n : E'_n \to \mathcal{E}_n$ induces an isomorphism

$$(E'_n / E_n^0)^\psi \simeq (\mathcal{E}_n / \mathcal{E}_n^p)^\psi$$

for any $a \geq 0$. Therefore $\mathcal{E}_n^\psi$ has no nontrivial torsion element.
Lemma 1.

Proof. By (C1) and (C2), we obtain the following exact sequence for holds for all $n \geq n_0$.

We give an outline of a proof for convenience of the readers.

Proof. By (C1) and (C2), we obtain the following exact sequence for $m \geq n$ (cf. [15 §2]):

$$0 \rightarrow H^1(\Gamma_n, E_m) \rightarrow A_n^\psi \rightarrow (A_m^\Gamma_n) \rightarrow H^2(\Gamma_n, E_m) \rightarrow 0,$$

where $E_n$ is the group of units of $K_n$ and $\Gamma_n = \Gamma_{\psi}$. If Greenberg’s conjecture holds for $A_n^\psi$, we can take $m$ and $n$ ($m \geq n$) such that $N_{m,n} : A_n^\psi \simeq A_m^\psi$ and that $i_{n,m} : A_n^\psi \rightarrow (A_m^\Gamma_n)\psi$ is a zero map, where $i_{n,m}$ is the induced map by the natural inclusion $k_n \rightarrow k_m$ (see [2 Proposition 1]). Since we have $H^2(\Gamma_n, E_m)\psi \simeq (E_n/N_{m,n}E_m)\psi$, 

$$0 \rightarrow A_m^\psi \rightarrow (E_n/N_{m,n}E_m)\psi \rightarrow 0.$$ 

Further, we have $C_n = N_{m,n}C_m \subseteq N_{m,n}E_m$ and $\#A_m^\psi = \#((E_m/C_m)(p))\psi = \#((E_n/C_n)(p))\psi$ for $n \geq n_0$ by Mazur-Wiles’ theorem, where $A(p)$ is the $p$-part of the finite abelian group $A$. Therefore we have $A_n^\psi \simeq A_m^\psi \simeq ((E_n/C_n)(p))\psi \simeq ((E_m/C_m)(p))\psi$. 

Let $L_n(\psi^*)$ be the fixed subfield of $L_n$ by $\bigoplus_{\chi \neq \psi} X_n^\chi$. In a similar way, we define $M_n(\psi^*)$, $L_{\infty}(\psi^*)$, etc. For an ideal $\mathfrak{L}$ of $K_n$, set $\sigma^\psi_{\mathfrak{L}} = \left(\frac{L_n(\psi^*)/K_n}{\mathfrak{L}}\right) \in (X_n/\bigoplus_{\chi \neq \psi} X_n^\chi) \simeq X_n^\psi$, where $(\cdot)$ is the Artin symbol. In order to calculate $(E_n/C_n)\psi$, we use the following lemma:

Lemma 1. For $k \leq n + 1$, if $c_n \in C_n^r$ satisfies

(A) \[ d_n(c_n) \in \left(\mathcal{U}_n^k\right)^\psi C_n^k, \]

then $\sqrt[p]{c_n} \in L_n(\psi^*)$. Further assume that

(B) \[ X_n^\psi \text{ is generated by } \sigma^\psi_{\mathfrak{L}}, \text{ for } \mathfrak{L} \mid p \text{ and } 1 \leq i \leq r. \]

Then \[ c_n \in E_n^r \psi^k \text{ if and only if } (c_n \mod \mathfrak{L}_i)_{1 \leq i \leq r} \in \bigcap_{i=1}^r (\mathcal{O}_{K_n}/\mathfrak{L}_i)^{p^k}. \]

Proof. Since $\sqrt[p]{c_n} \in M_n(\psi^*)$, (A) implies the former assertion. By (B), $K_n(\sqrt[p]{c_n}) = K_n$ if and only if the splitting field of $\mathfrak{L}_i$ in $L_n(\psi^*)/K_n$ includes $K_n(\sqrt[p]{c_n})$ for every $i$, i.e., $c_n$ is a $p^th$ power at $\mathfrak{L}_i$. Therefore we obtain the latter assertion. 

In [15], when $\psi^*(p) \neq 1$, we gave explicit conditions for (A) and (B) by using cyclotomic units, Gauss sums and prime numbers. When $\psi^*(p) = 1$, $\omega_0$ divides $g_\psi(T)$. For $n = 0$, we can obtain full information from Gauss sums of a subfield of $K_0$ (cf. [11]). However, for $n \geq 1$, we cannot directly obtain full information on $A_n^\psi$ from Gauss sums (see [7] §4 and the last example of section 3). So we will replace the conditions (A) and (B) with (A) and (B) in Lemma [4].
Let us write the Kummer pairing:

\[ X^{\psi^*}_\infty \times W^{\psi}_\infty \to \mu_{p^\infty} = \bigcup (\zeta_{p^n}), \]

where \( W_\infty \) is the subgroup of \( K^{\psi}_\infty \otimes Q_p / Z_p \) which corresponds to \( X_\infty \) via Kummer theory. Let \( \text{Ker}_{X^{\psi^*}_\infty} \omega_0 \) be the subgroup of \( X^{\psi^*}_\infty \) consisting of all elements annihilated by \( \omega_0 \). Set \( \tilde{X}^{\psi^*}_\infty = X^{\psi^*}_\infty / \text{Ker}_{X^{\psi^*}_\infty} \omega_0 \). By Ferrero-Greenberg’s theorem in [3], \( \omega_0 \) does not divide \( \tilde{g}_\psi(T) = g_\psi^*(T) / \omega_0 \). Hence we have

\[ \varphi : X^{\psi^*}_\infty \to \bigoplus_{i=1}^s \Lambda / (g_i^*(T)) \oplus \Lambda / (\omega_0), \]

where \( \prod_{i=1}^s g_i^*(T) = \tilde{g}_\psi^*(T) \). Let \( \pi \) be the projection from \( \bigoplus_{i=1}^s \Lambda / (g_i^*(T)) \oplus \Lambda / (\omega_0) \) to \( \bigoplus_{i=1}^s \Lambda / (g_i^*(T)) \). Then \( \tilde{X}^{\psi^*}_\infty \simeq (\varphi(X^{\psi^*}_\infty)(\Lambda / (\omega_0))/((\Lambda / (\omega_0))) \simeq \pi(\varphi(X^{\psi^*}_\infty)). \) Hence \( \tilde{X}^{\psi^*}_\infty \) has no nontrivial finite submodule (cf. [10] Theorem 18) and \( \text{char}_A(\tilde{X}^{\psi^*}_\infty) = \tilde{g}_\psi^*(T) \). Set \( \tilde{W}^{\psi}_\infty = \omega_0^* \tilde{W}^{\psi}_\infty \). Then we have the following Kummer pairing:

\[ \tilde{X}^{\psi^*}_\infty \times \tilde{W}^{\psi}_\infty \to \mu_{p^\infty}. \]

When \( \psi^*(p) = 1 \), we consider the above paring. In order to obtain elements in \( \tilde{W}^{\psi}_\infty \) satisfying (A) in Lemma [4] we use the following lemma:

**Lemma 2.** For integers \( n \) and \( k \), we set

\[ C_{n,k} = \{ [c_n] \in (C_n^k E_n^k / E_n^k)^\psi | d_n(c_n) \in (U_{p^{n+k}}^n \mathcal{T}_n)^\psi C_n^k \}. \]

Let \( a \) be the minimum integer such that \( p^a \in (\omega_0^*, \tilde{g}_\psi(T)) \). Then

\[ p^a C_{n,k} \subseteq \omega_0^* C_{n,k} \subseteq C_{n,k}. \]

Assume that Greenberg’s conjecture holds for \( A_n^\psi \). Then

\[ \bigcup_{n,k} C_{n,k} = \tilde{W}^{\psi}_\infty. \]

**Proof.** By Ferrero-Greenberg’s theorem, \( \omega_0^* \) does not divide \( \tilde{g}_\psi(T) \). Therefore the minimum integer \( a \) exists. Write \( p^a = \omega_0^* a(T) + \tilde{g}_\psi(T) b(T) \) for \( a(T), b(T) \in \Lambda \). Then we have \( d_n(c_n) p^a = d_n(c_n) \omega_0^* a(T) d_n(c_n) \tilde{g}_\psi(T) b(T) \in C_n^k \mathcal{T}_n^k \mathcal{T}_n \). Since \( C_n \cap \mathcal{T}_n = \{ 1 \} \), we have \( p^a [c_n] \in \omega_0^* C_n. \) Since \( \mathcal{T}_n = \mathcal{T}_{n+k} \), \( d_{n+k}(c_n) \) is a \( p \)-th power in \( \mathcal{U}_{n+k} \) for \( [c_n] \in C_{n,k} \). Therefore we have \( C_{n,k} \subseteq \tilde{W}^{\psi}_\infty \) and \( p^a C_{n,k} \subseteq \tilde{W}^{\psi}_\infty \). Let

\[ C'_{n,k} = \{ [c_n'] \in (C_n/C_n^k)^\psi | d_n(c_n) \in (U_{p^{n+k}}^n \mathcal{T}_n)^\psi C_n^k \}. \]

By Fact 1, for sufficiently large integers \( n \), \( C'_{n,k} \simeq (Z/p^k Z)^{\lambda(\psi)} \). If Greenberg’s conjecture holds, \( \tilde{z}(C_{n,k}) \) is bounded. Hence \( C_{n,k} \) has a subgroup which is isomorphic to \( (Z/p^{k-k'} Z)^{\lambda(\psi)} \), where \( k' \leq k \) is a constant integer. Further the natural map \( i_{n,m} : C_{n,k} \to C_{m,k+m-n} \) \( ([c_n] \mapsto [c_n p^{m-n}]) \) is injective. Therefore \( i_{n,m}(C_{n,k}) \subseteq p^a C_{m,k+m-n} \) for sufficiently large integers \( m \). Since \( \bigcup C_{n,k} \simeq (Q_p / Z_p)^{\lambda(\psi)} \simeq \tilde{W}^{\psi}_\infty \), we have the equality. \( \square \)
Let \( \tilde{L}_\infty(\psi^*) \) be the fixed subfield of \( L_\infty(\psi^*) \) by \( \text{Ker} X_{\psi^*}^\infty : \omega_0 \). Set \( \tilde{L}_n(\psi^*) = L_n(\psi^*) \cap \tilde{L}_\infty(\psi^*) \) and \( \tilde{X}_n^{\psi^*} = \text{Gal}(\tilde{L}_n(\psi^*)/K_n) \simeq \hat{X}_n^{\psi^*} \). Then we can write
\[
\tilde{X}_n^{\psi^*} \simeq \hat{X}_n^{\psi^*} \cap \nu_{n,0} \hat{Y}_\infty^{\psi^*}
\]
for a submodule \( \tilde{Y}_\infty^{\psi^*} \) of \( \hat{X}_\infty^{\psi^*} \) (see [17] Lemma 13.15).

Let \( m = (p,T) \) be the maximal ideal of \( \Lambda \). In order to find ideals \( \mathfrak{L}_i \) satisfying (\( \mathcal{B} \)) in Lemma 4, we use the following lemma.

**Lemma 3.** Let \( X \) be a finitely generated torsion \( \Lambda \)-module which has no nontrivial finite \( \Lambda \)-submodule. Assume that \( \omega_0 \) does not divide \( \text{char} A(X) \). Then for any \( \Lambda \)-submodules \( X' \) and \( Z \) of \( X \) such that \( Z \subseteq \omega_0 X, (\omega_0 X + Z)/Z = (\omega_0 X' + Z)/Z \) holds if and only if \( X = X' \).

**Proof.** Since \( m(\omega_0 X) \supseteq Z \), we have \( \omega_0 X = \omega_0 X' \) by Nakayama’s lemma. For any element \( x \in X \), there exists \( x' \in X' \) such that \( \omega_0 x = \omega_0 x' \). Since \( \omega_0 : X \to X (x \mapsto \omega_0 x) \) is injective, we have \( x = x' \) and \( X = X' \). \( \square \)

In order to calculate \( (E_n/C_n)^{\psi^*}(p) = 1 \), we use the following lemma, which can be proved in a similar way to Lemma 14.

**Lemma 4.** Assume that Greenberg’s conjecture holds for \( A_n^{\psi^*} \). For \( k \leq n + 1 \), if \( c_n \in C_n^{\prime} \) satisfies
\[
A_n^{\psi^*}(p) \subseteq (U_n^{\psi^*} T_n^{\psi^*})^{\psi^*} C_n^{\psi^*},
\]
then \( \sqrt[n']{c_n} \in \tilde{L}_n^{\psi^*}(\psi^*) \) for some \( n' \). Further assume that

**(B)** \( \tilde{X}_n^{\psi^*} \) is generated by \( \tilde{\sigma}_n^{\psi^*} \) for \( \mathfrak{L}_i \uparrow p \) and \( 1 \leq i \leq r \).

Then
\[
c_n \in E_n^{\prime} C_n^{\psi^*}
\]
if and only if \( (c_n \mod \mathfrak{L}_i)_{1 \leq i \leq r} \in \prod_{i=1}^{r} (\mathcal{O}_{K_n}/\mathfrak{L}_i)^{p^k} \).

By Mazur-Wiles’ theorem, we can obtain \( \sharp A_n^{\psi^*} = \sharp X_n^{\psi^*} = \sharp (X_\infty^{\psi^*}/\nu_{n,0} Y_\infty^{\psi^*}) \) from generalized Bernoulli numbers. However it is difficult to compute \( \sharp \tilde{X}_n^{\psi^*} \) because it is difficult to determine \( \tilde{Y}_\infty^{\psi^*} \) in \( \hat{X}_\infty^{\psi^*} \). Therefore, in general, we have a difficulty in checking (\( \mathcal{B} \)) by our method.

3. **Numerical examples of ideal class groups**

Let \( \chi \) be an odd primitive quadratic Dirichlet character, \( f_\chi \) the conductor of \( \chi \), and \( p \) an odd prime number. Set \( F = \mathbb{Q} = \mathbb{Q}(\sqrt{f_\chi}) \) and \( K = \mathbb{Q}(\sqrt{f_\chi}, \zeta_p) \). Let \( k \) be an odd integer with \( 3 \leq k \leq p - 2 \). Then \( \chi \omega^k \) is an even character. For a pair \( (p, \chi \omega^k) \), we set the following condition:

**C** \( \chi \omega^k(p) \neq 1 \) and \( \chi \omega^{1-k}(p) \neq 1 \).

If \( \chi \omega^k(p) \neq 1 \), we have \( \lambda_p(\chi \omega^k) = \lambda_p(\chi \omega^k) \) and \( \nu_p(\chi \omega^k) = \nu_p(\chi \omega^k) \). In the range \( 1 < f_\chi < 200, 5 \leq p < 100000 \) and odd integers \( k \) with \( 3 \leq k \leq p - 2 \), there are 14085400622 pairs of \( (p, \chi \omega^k) \) satisfying (C). Among them, 296975 pairs satisfy \( \lambda_p(\chi \omega^k) = 1 \), 43 pairs \( \lambda_p(\chi \omega^k) = 2 \), and two pairs \( \lambda_p(\chi \omega^k) = 3 \). By the method of [3], we verified Greenberg’s conjecture, i.e., \( \lambda_p(\chi \omega^k) = 0 \) for each of them. Moreover, we checked \( \nu_p(\chi \omega^k) \leq 2 \) by the method of [16]. In the above range, 44 pairs do not satisfy (C). For these cases, we also checked that \( \lambda_p(\chi \omega^k) = \)
that \( \lambda_p(\omega) = \nu_p(\omega) = 0 \) for all \( f_x \) and \( p \) in the above range.

**Proposition 1.** If \( A_0^\omega \) is trivial, then \( A_n^\omega \) is trivial for every \( n \geq 0 \).

**Proof.** Assume that \( A_n^\omega \) is not trivial for some \( n \). Then we have \( \deg g_\omega^\omega(T) = \deg g_\omega(T) \geq 1 \). Hence, if \( \chi(p) \neq 1 \), we have \( \nu_p(\lambda A_0^\omega) = \nu_p(g_\omega^\omega(0)) \geq 1 \). If \( \chi(p) = 1 \), then \( \omega \neq p \neq 1 \). In this case, by the class field theory (see [8, Lemma 3]), \( A_n^\omega \neq 0 \) implies \( A_n^\omega \neq 0 \). Let \( a \in c \in A_0^\omega \) such that \( a^p = (\alpha) \) for \( \alpha \in \mathcal{K} \). Further there exists \( \varepsilon \in E_0 \setminus E_0^p \) such that \( [\varepsilon] \in (E_0/E_0^p)^{\lambda} \). Then we have \( \sqrt{\alpha}, \sqrt{\varepsilon} \in \mathcal{M}_0(\chi) \) and \( \text{Gal}(K(\sqrt{\alpha}, \sqrt{\varepsilon})/K) \cong \mathbb{Z}/p\mathbb{Z} \oplus \mathbb{Z}/p\mathbb{Z} \). Since \( (\mathcal{U}_0/\mathcal{U}_0^p)^\chi \) there exists a nontrivial unramified abelian \( p \)-extension of \( K \) contained in \( M_0(\chi) \). Therefore, by the class field theory, \( A_n^\omega \) is trivial.

We obtain the following computational result:

**Proposition 2.** Let \( K_{f_x,p} \) be the maximal real subfield of \( \mathbb{Q}(\sqrt{-f_x}, \zeta_p) \). \( \lambda_p(K_{f_x,p}) = 0 \) for all \( 1 < f_x < 200 \) and \( 5 \leq p < 100000 \). Exactly,

- \( A_0(K_{f_x,p}) = \{0\} \) for \( n \geq 0 \) and \( (f_x,p) \) which does not appear in Table 1,
- \( A_n(K_{f_x,p}) \cong \mathbb{Z}/p\mathbb{Z} \) for \( n \geq 0 \) and \( (f_x,p) \neq (136,11) \) in Table 1,
- \( A_n(K_{f_x,p}) \cong \{ \mathbb{Z}/p^2\mathbb{Z} \} \) for \( n \geq 0 \), and \( (f_x,p) = (136,11) \).

\[
\begin{array}{cccc}
\text{Table 1. } \nu_p(\omega^k) = 1 \text{ (2 for the *-marked case)} & \nu_p(a_0^k) = 2 \text{ (3 for the *-marked case)}
\end{array}
\]

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Table 3. $v_p(b_0(\chi\omega^k)) = 2$

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Table 4. $\tilde{\lambda}_p(\chi\omega^k) = 2$ (3 for the $*$-marked cases)

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</table>

Table 5. The $\chi$-irregularity index density

<table>
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<th>$n'_r$</th>
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<th>the density'</th>
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From these tables, we can obtain concrete information on the higher $K$-groups of the ring of integers of $\mathbb{Q}(\sqrt{-f_\chi})$ (see [16] §4).

Let us call a pair of integers $(p, k)$ a $\chi$-irregular pair if $p$ is a prime, $k$ is an odd integer satisfying $3 \leq k \leq p - 2$, $p$ divides $a_0(\chi\omega^k) = L_p(1, \chi\omega^k)$ (or $b_0(\chi\omega^k) = L_p(0, \chi\omega^k)$), and $(p, \chi\omega^k)$ satisfies (C). Further we define the $\chi$-irregularity index $r_p(\chi)$ by

$$r_p(\chi) = \sharp\{(p, k)|(p, k) \text{ is a } \chi\text{-irregular pair}\}.$$
We call a prime number $p$ $\chi$-irregular if $r_p(\chi) > 0$. Let $m_p(\chi)$ be the number of even integers $k$ with $3 \leq k \leq p - 2$ such that $(p, \chi^k)$ satisfies (C). We define

$$n_r = \sum_{(\chi, p) \text{ s.t. } r_p(\chi) = r} 1$$

and

$$n'_r = \sum_{\chi, p} m_p(\chi) C_r \left( \frac{1}{p} \right)^r \left( \frac{p - 1}{p} \right)^{m_p(\chi) - r},$$

where $\chi$ runs over all odd quadratic characters with $1 < f_\chi < 200$, and $p$ runs all prime numbers with $5 \leq p < 100000$. The distribution of the indices of $\chi$-irregularity is given in Table 5. The actual numbers $n_r$ seem to be close to the expected numbers $n'_r$ (cf. [2] and [17, p. 63]).

In Figure 1, we compare the actual numbers of exceptional pairs with the expected numbers in the range $200 < p < 100000$. Set

$$\nu(x) = \sharp\{(p, \chi^k)|200 < p < x, \chi^k; \text{even, } k \neq 1, \nu_p(\chi^k) > 1\},$$

$$a_0(x) = \sharp\{(p, \chi^k)|200 < p < x, \chi^k; \text{even, } k \neq 1, a_0(\chi^k) \geq 2\},$$

$$b_0(x) = \sharp\{(p, \chi^k)|200 < p < x, \chi^k; \text{even, } k \neq 1, b_0(\chi^k) \geq 2\},$$

$$\text{lmd}(x) = \sharp\{(p, \chi^k)|200 < p < x, \chi^k; \text{even, } k \neq 1, \tilde{\lambda}_p(\chi^k) \geq 2\},$$

$$E(x) = \left[ \sharp\{\chi\} \sum_{200 < p < x, p \text{ prime}} \frac{p - 3}{2p^2} \right],$$

where $[\ast]$ is the Gauss symbol and $\chi$ runs over all odd quadratic characters with $1 < f_\chi < 200$. 

**Figure 1.** Exception pairs (odd quadratic, $1 < f < 200$, $200 < p < 100000$)
In order to increase the number of samples, we combine the above data with that in [16], and obtain Figure 2. Set

\[ \nu(x) = \sharp \{ (p, \chi \omega^k) | 200 < p < x, \chi \omega^k \text{ even, } k \neq 0, \ 1, \nu_p(\chi \omega^k) \geq 1 \}, \]

\[ a_0(x) = \sharp \{ (p, \chi \omega^k) | 200 < p < x, \chi \omega^k \text{ even, } k \neq 0, \ a_0(\chi \omega^k) \geq 2 \}, \]

\[ b_0(x) = \sharp \{ (p, \chi \omega^k) | 200 < p < x, \chi \omega^k \text{ even, } k \neq 0, \ b_0(\chi \omega^k) \geq 2 \}, \]

\[ \text{lmd}(x) = \sharp \{ (p, \chi \omega^k) | 200 < p < x, \chi \omega^k \text{ even, } k \neq 0, \ 1, \ \lambda_p(\chi \omega^k) \geq 2 \}, \]

\[ E(x) = \left[ \frac{\sharp \{ \chi \} \sum_{200 < p < x, \ p \text{ prime}} \frac{p - 3 \ 1}{2 p^2}}{2} \right], \]

where \( \chi \) runs over all quadratic characters with \( 1 < f_\chi < 200 \).

From our data, the actual numbers seem to be close to the expected numbers. Even for large \( p \), it might be possible that the actual numbers are near to the expected numbers.

Finally we give an example such that \( A_n \) is not cyclic. In [11], Aoki-Fukuda showed that

\[ A_0^{\chi^\omega} \simeq \mathbb{Z}/p\mathbb{Z} \oplus \mathbb{Z}/p\mathbb{Z}, \quad A_0^{\chi^3} \simeq \{ 0 \} \]

for \( (f_\chi, p) = (4 \cdot 14606, 5) \) by using cyclotomic units of \( \mathbb{Q}(\zeta_{f_\chi l_1}) \) (\( l_1 = 11251 \) and \( l_2 = 22501 \)). By our method (using cyclotomic units and Gauss sums of \( \mathbb{Q}(\zeta_{f_n}) \) for \( n \leq 2 \)), we show the above and

\[ A_n^{\chi^\omega} \simeq \mathbb{Z}/p^2\mathbb{Z} \oplus \mathbb{Z}/p\mathbb{Z}, \quad A_n^{\chi^3} \simeq \{ 0 \} \]

for \( n \geq 1 \). First we have

\[ \begin{cases} g_{\chi^\omega}(T) \equiv \omega_0(T^2 + 2380T + 2025) \pmod{p^5}, \\ g_{\chi^\omega}^3(T) \equiv \omega_0(T^2 + 1305T + 2150) \pmod{p^5}, \end{cases} \]

\[ g_{\chi^\omega}^3(T) = 1, \quad g_{\chi^\omega}^3(T) = 1. \]
Hence we immediately obtain the triviality of $A_n^{\omega^3}$. For $\psi = \chi \omega$, we have $\psi(p) \neq 1$ and $\psi^*(p) = 1$.

**Cyclotomic units.**

$n = 0$

$$C_0^\psi \simeq (\omega_0, p^2)/(\omega_0),$$

$$E_0^\psi \simeq (E_0^\psi)' \subseteq A/(\omega_0).$$

Hence $(E_0/C_0)^\psi$ is a subgroup of $A/(\omega_0, p^2) \simeq \mathbb{Z}/p^2\mathbb{Z}$.

$n = 1$

$$C_1^\psi \simeq (\tilde{g}_\psi(T), pT, p^3)/(\omega_1).$$

Let $l_1 = 1 + 12f_1p = 87636001$ and $l_2 = 1 + 22f_1p = 160666001$. By studying the image of $C_1^\psi$ in $\prod_{\mathfrak{p}}(O_{K_1/\mathfrak{p}})$, we have

$$E_1^\psi \simeq (E_1^\psi)' \subseteq (\tilde{g}_\psi(T), T, p)/(\omega_1).$$

Hence $(E_1/C_1)^\psi$ is a subgroup of $(\tilde{g}_\psi(T), T, p)/(\tilde{g}_\psi(T), pT, p^3) \simeq \mathbb{Z}/p\mathbb{Z} \oplus \mathbb{Z}/p\mathbb{Z}$.

$n = 2$

$$C_2^\psi \simeq (\tilde{g}_\psi(T), p^2T, p^4)/(\omega_2).$$

Let $l'_1 = 1 + 8f_2p = 292120001$ and $l'_2 = 1 + 14f_2p = 511210001$. By studying the image of $C_2^\psi$ in $\prod_{\mathfrak{p}}(O_{K_2/\mathfrak{p}})$, we have

$$E_2^\psi \simeq (E_2^\psi)' \subseteq (\tilde{g}_\psi(T), pT, p^2)/(\omega_2).$$

Hence $(E_2/C_2)^\psi$ is a subgroup of $(\tilde{g}_\psi(T), pT, p^2)/(\tilde{g}_\psi(T), p^2T, p^4) \simeq \mathbb{Z}/p\mathbb{Z} \oplus \mathbb{Z}/p\mathbb{Z}$.

This implies Greenberg’s conjecture for $A_n^\psi$.

By computation of Gauss sums, we will show that $E_1^\psi \simeq (\tilde{g}_\psi(T), T, p)/(\omega_1)$.

Hence we have $\mathbb{Z}(E_1^\psi/C_1^\psi) = p^3$, $\mathbb{Z}(E_2^\psi/C_2^\psi) \geq p^3$, and $E_2^\psi \simeq (\tilde{g}_\psi(T), pT, p^3)/(\omega_2)$. By this isomorphism, $\text{Ker}(A_0 \to A_2)^\psi \simeq H^1(\Gamma_0, E_2)^\psi \simeq \mathbb{Z}/p\mathbb{Z} \oplus \mathbb{Z}/p\mathbb{Z}$ (see the proof of Theorem 1). Therefore we have $A_0^\psi \simeq \mathbb{Z}/p\mathbb{Z} \oplus \mathbb{Z}/p\mathbb{Z}$ and $A_1^\psi \simeq \mathbb{Z}/p\mathbb{Z} \oplus \mathbb{Z}/p\mathbb{Z}$ for $n \geq 1$ (cf. [15, Theorem 1]).

**Gauss sums.** Since $p\omega_0 \in (\tilde{g}_\psi(T), \omega_1)$, the exponent of $\omega_0 X_\infty^\psi/\omega_1 X_\infty^\psi \simeq \omega_0 X_\infty^\psi/\omega_1 X_\infty^\psi$ is $p$. Therefore, the exponent of $\omega_0 A_1^\psi$ is at most $p$. We will show that $\omega_0 A_1^\psi \simeq \mathbb{Z}/p\mathbb{Z} \oplus \mathbb{Z}/p\mathbb{Z}$ by using Gauss sums and prime numbers.

Set $h(T) = 21T^4 + 17T^3 + 9T^2 + 5T + 15$. Then we have

$$h(T)g_\psi^*(T) \equiv p\omega_0 \mod (\omega_1, p^2).$$

Let $e_{\psi^*, m} \in \mathbb{Z}[[\Delta]]$ such that $e_{\psi^*, m} \equiv c_{\psi^*} \mod p^m$. For $\mathcal{L}_{1}\mid l_1l_2$, let $g_1(\mathcal{L}_1)$ be the Gauss sum of $K_1$ which satisfies

$$(g_1(\mathcal{L}_1)e_{\psi^*, m}) \equiv \mathcal{L}_1^{f_{\psi^*}}_{\psi^*, m},$$

where $\theta_1 \in \mathbb{Q}[\text{Gal}(K_1/\mathbb{Q})]$ is the Stickelberger element (see [4] pp. 42-45 for details). Hence for any integer $m \geq 1$, there exists $g'_m \in K_1$ such that

$$(g_1(\mathcal{L}_1)e_{\psi^*, 1}) \equiv \mathcal{L}_1^{f_{\psi^*}}_{\psi^*, m}(g'_m \psi^*).$$

Since $G_1^*(T) \equiv e_{\psi^*, m}\theta_1 \mod (p^m, \omega_1)$, we have

$$(g_1(\mathcal{L}_1)e_{\psi^*, 1}h(T)) = \mathcal{L}_1^{\omega_0\nu(T)e_{\psi^*, m}} \mathcal{L}_1^{\nu_{\mathfrak{p}}e_{\psi^*, m}}(g'_m \psi^*)$$
for $u(T) \in \mathbb{A}_\mathbf{Q}$ and $v \in \mathbb{Z}_p[\text{Gal}(K_1/\mathbb{Q})]$. Let $l_1 = 1 + 11f_1 = 16066601$, $l_2 = 1 + 14f_1 = 20448401$, $l'_1 = 1 + 4(2f_1l_1l_2) = 383888095771419568401$ and $l'_2 = 1 + 7(2f_1l_1l_2) = 671804167599842448401$. By studying the images of $g_1(\mathcal{L}_i)^{\psi_{i,n'}, T^h(\mathbf{T})}$ in \( \prod_{i' | l'_2} (\mathcal{O}_{K_{l_1l_2}}/\mathcal{L}_i^{n'}) \), we conclude that the classes of $\mathcal{L}_i^{\psi_{i,n'}, T^h(\mathbf{T})}$ for $\mathcal{L}_i | l_1 l_2$ generate a subgroup of $\hat{\mathbb{A}}^f_{\mathbf{Q}}$ whose quotient is isomorphic to $\mathbb{Z}/p\mathbb{Z} \oplus \mathbb{Z}/p\mathbb{Z}$. Since $\zeta(\omega L/\omega_1 X^{\psi}) = p^2$, this happens only when $\nu_1, \nu_2 \omega_1 X^{\psi} = \omega_1 X^{\psi}$, i.e. $Y^{\psi} = \omega_0 X^{\psi}$. By Lemma 3 ($X = \bar{X}^{\psi}$ and $Z = \omega_1 \bar{X}^{\psi}$) and the class field theory, we have $(\sigma_{\mathcal{L}_i}^{\psi_{i,n'}, T^h(\mathbf{T})})_{\mathcal{L}_i | l_1 l_2} = \hat{X}^{\psi}$. By Lemma 4 ($n = n' = 1$) and the image of $C_1^0$ in $\prod_{l_1 l_2} (\mathcal{O}_{K_1}/\mathcal{L}_i)$, we obtain $E_1^0 \simeq (g_{\psi}(T), T, p)/\langle \omega_1 \rangle$.

We used thirty personal computers for three months to make the tables in this section. The programs were written in UBASIC and C, in which the GNU MP library was included. For the last example, it took a few minutes to calculate cyclotomic units modulo prime ideals, and thirty minutes to calculate Gauss sums modulo prime ideals on one PC (CPU: Pentium IV, 3.6GHz, RAM 2GB). In [1], it took 6 hours and 42 minutes to compute $A_0$ by using Alpha 21264, 667MHz, RAM 4GB.

References


Faculty and School of Engineering, The University of Tokushima, 2-1 Minamijosanjima-cho, Tokushima 770-8506, Japan
E-mail address: hiroki@pm.tokushima-u.ac.jp