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We consider here the zeta function for a function field defined over a finite field F_p. For each inter j, $\zeta(j)$ is a polynomial over F_p, as is $\zeta'(j)$, the "derivative" of zeta. In this note we compute the degree of these polynomials, determine when they are the constant polynomial and relate them to the polynomial gamma function.

In a recent series of papers D. Goss has introduced the notion of a zeta function $\zeta(j)$ for rational function fields over F_r, where $r = p^k$, with p a rational prime. In particular, for each positive integer i, with $i \not\equiv 0$ $(r-1)$, $\zeta(-i) \in F_r[t]$. Goss also defines the "derivative" of ζ, ζ', with $\zeta'(-i) \in F_r[t]$ if $i \equiv 0$ $(r-1)$. We combine these special values of ζ and ζ' into a single function $\beta(n)$ (with $n = -i$) defined by:

$$\beta(0) = 0, \qquad \beta(1) = 1, \tag{1}$$
$$\beta(n) = 1 - \sum_{\substack{i=1 \\ i \equiv n(s)}}^{n-1} \binom{n}{i} t^i \beta(i), \qquad n \geq 2,$$

where $s = r - 1$. Thus, by (3.9) and (3.10) of [2],

$$\beta(n) = \begin{cases} \zeta(-n), & n \not\equiv 0\,(s) \\ \zeta'(-n), & n \equiv 0\,(s) \end{cases}. \tag{2}$$

An important situation where these functions arise is in determining the class numbers of certain extension fields over $F_r[t]$ (modeled on cyclotomic fields). If P is a prime polynomial in $F_r[t]$, Goss defines class numbers $h^+(P)$ and $h^-(P)$ associated to P, in the classical fashion, and shows that their study (à la Kummer) involves the polynomials $\zeta(-i)$ and $\zeta'(-i)$. Thus it is important that we know certain facts about these functions, and hence about $\beta(n)$. Specifically, when is $\beta(n) = 1$? What is the degree of $\beta(n)$? When does $\beta(n)$ factor? In this note we give some answers to these questions, for the case $r = p$.

REMARK. I am indebted to Goss for bringing this material to my attention.

The function $\beta(n)$. Let p be a rational prime, and for each integer $n \geq 0$, let $\beta(n) \in F_p[t]$ be the polynomial defined above. Note that if $0 < n \leq s \, (= p - 1)$, then $\beta(n) = 1$. For $n > s$ we rewrite (1) as follows: set $k = [(n-1)/s]$. Then (1) becomes:

$$\beta(n) = 1 - \sum_{i=1}^{k} \binom{n}{is} t^{n-is} \beta(n - is). \tag{3}$$

Let $n = \sum_i a_i p^i$ be the p-adic representation of n; thus, $0 \leq a_i \leq s$, and almost all a_i are zero. Define

$$l(n) = \sum_i a_i.$$

Our first result is:

THEOREM 1. *Let n be a positive integer with $l(n) \leq s$. Then,*

$$\beta(n) = 1.$$

The proof depends upon several simple facts about binomial coefficients mod p. Recall the result of Lucas:

(4) *If m and n are given p-adically by $m = \sum_i b_i p^i$, $n = \sum_i a_i p^i$, then*

$$\binom{n}{m} \bmod p \equiv \prod_i \binom{a_i}{b_i} \bmod p.$$

In particular,

$$\binom{n}{m} \not\equiv 0 \bmod p \Leftrightarrow 0 \leq b_i \leq a_i, \text{ all } i.$$

As an immediate consequence, we have:

(5) *If $\binom{n}{m} \not\equiv 0 \bmod p$, then $l(n) = l(m) + l(n-m)$. In particular, if $1 \leq m < n$, then $l(n) > l(m)$.*

Finally, note that since $p \equiv 1 \bmod s$, we have:

$$n \equiv l(n) \mod s. \tag{6}$$

Proof of Theorem 1. Let j be any positive integer. By (6), since $js \equiv 0 \bmod s$, $l(js) \geq s$. Thus, if n is an integer with $js < n$ and $\binom{n}{js} \not\equiv 0 \bmod p$, then by (5), $l(n) > l(js) \geq s$. Therefore, if $l(n) \leq s$, then $\binom{n}{js} \equiv 0 \bmod p$. Thus, by (3), $\beta(n) = 1$, as claimed.

We suppose now that n is an integer with $l(n) > s$; our goal is to calculate the degree of $\beta(n)$ — call this simply $D(n)$.

Define an integer valued function $\rho(n)$ by:

(7) *If $l(n) \geq s$, set $\rho(n) = n - m$, where m is the least positive integer such that*

$$l(m) = s \quad \textit{and} \quad \binom{n}{m} \not\equiv 0 \ (p).$$

Thus, if n is written p-adically in the form

$$n = \sum_{i=0}^{N} p^{e_i}, \quad \text{with } e_0 \leq \cdots \leq e_N, \tag{8}$$

and with no more than s e_i's with the same value, then

$$m = \sum_{i=0}^{s-1} p^{e_i}.$$

If q is an integer (≥ 0) with $l(q) < s$, set $\rho(q) = 0$.

Set $\rho^{i+1}(n) = \rho(\rho^i(n))$, with $\rho^0(n) = n$. Thus, for large i, $\rho^i(n) = 0$.

EXAMPLE. $p = 5$, $n = 3 \cdot 1 + 4 \cdot 5 + 2 \cdot 5^3$. Then,

$$\rho^1(n) = 3 \cdot 5 + 2 \cdot 5^3,$$

$$\rho^2(n) = 5^3,$$

$$\rho^3(n) = 0.$$

Our result is:

THEOREM 2. *Let n be an integer with $l(n) > s$. Then*

$$D(n) = \text{degree}\,\beta(n) = \sum_{i \geq 1} \rho^i(n).$$

The proof will be by induction on $l(n)$. Suppose first that $l(n) = s + 1$. If j is any positive integer with $js < n$ and $\binom{n}{js} \not\equiv 0 \bmod p$, then by (5) and (6), $l(n - js) = 1$, and so by Theorem 1, $\beta(n - js) = 1$. Therefore, by (2), $D(n) = n - js$, where j is the *least* positive integer such that $\binom{n}{js} \not\equiv 0 \ (p)$; i.e., $D(n) = \rho(n)$, as stated in Theorem 2.

We now make the following pair of inductive hypotheses: let k be an integer $\geq s + 1$, and suppose that n is any integer such that

$$s + 1 \leq l(n) \leq k.$$

(A_k) For any such integer n, $D(n)$ is given by Theorem 2.

(B_k) Let n be any integer as above. If c is the least positive integer such that $\binom{n}{cs} \not\equiv 0\ (p)$ and d is any integer with $cs \leq ds \leq n$ and $\binom{n}{ds} \not\equiv 0\ (p)$; then $D(n - cs) \geq D(n - ds)$.

Claim 1. A_k *implies* B_{k+1}.

Proof. Write n as in (8) so that $cs = \sum_{i=0}^{s-1} p^{e_i}$. Thus, $n - cs = \sum_{i=0}^{N-s} p^{f_i}$, where $f_i = e_{i+s}$. Similarly, write $n - ds = \sum_{i=0}^{M} p^{g_i}$, where $M \leq N - s$. Then, for $i \leq M$, $p^{f_i} \geq p^{g_i}$, and so $D(n - cs) \geq D(n - ds)$, either by Theorem 1 or by A_k and Theorem 2, since $l(n - cs)$ and $l(n - ds)$ are less than $l(n)$.

Claim 2. A_k *and* B_{k+1} *imply* A_{k+1}.

Proof. Let n be an integer with $l(n) = k + 1$. Write n as in (8) and define cs as above, so that $\rho(n) = n - cs$. By (3) and B_{k+1},

$$D(n) = n - cs + D(n - cs) = \rho(n) + D(\rho(n)).$$

Since $l(\rho(n)) < l(n) = k + 1$, by A_k

$$D(\rho(n)) = \sum_{i\geq 1} \rho^i(\rho(n)) = \sum_{i\geq 1} \rho^{i+1}(n).$$

Therefore, $D(n) = \sum_{i\geq 1} \rho^i(n)$, which proves A_{k+1}.

Proof of Theorem 2. We showed above that A_{s+1} holds, and so by Claims 1 and 2, A_k holds for all $k > s$. This proves the theorem.

Note that (trivially) if n is positive, then $\beta(n) \neq 0$. Combining Theorems 1 and 2 we have:

COROLLARY 1. *If n is a positive integer, then $\beta(n) = 1$ if, and only if, $l(n) \leq s$.*

For certain values of n, $D(n)$ can be written out explicitly.

COROLLARY 2. *Let k and m be positive integers, with $m \leq s$. Then*

$$D\big((m + 1)p^k - 1\big) = s \cdot \sum_{i=1}^{k-1} ip^i + kmp^k.$$

Relation to the gamma function. We are interested in comparing the function $\beta(n)$ with the Gamma function Γ_n (see [**1**]). Combining Corollary 2 with (3.1.1) of [**1**], we find:

COROLLARY 3. *Let $n = (m+1)p^k - 1$, where k and m are positive integers with $m \le s$. Then,*

$$\deg \beta(n) = \deg \Gamma_n.$$

For certain values of n we have a stronger result.

THEOREM 3. *Suppose that $n = (m+1)p - 1$, with $1 \le m \le s$. Then,*

$$\beta(n) = 1 - \Gamma_n.$$

We are especially interested in divisibility properties of $\beta(n)$. Thus, we have:

COROLLARY 4. *For $1 \le k \le s/2$ and p an odd prime,*

$$\beta((2k+1)p - 1) = (1 - \Gamma_{kp})(1 + \Gamma_{kp}).$$

In particular,

$$\beta(p^2 - 1) = (1 - \Gamma_{sp/2})(1 + \Gamma_{sp/2}).$$

Proof of Theorem 3. We will need the following (easily proved) fact:

$$\text{If } 0 \le i \le s, \text{ then } \binom{s}{i} \equiv (-1)^i \bmod p.$$

Suppose that $n = (m+1)p - 1$, as above. Thus, $n = s \cdot 1 + mp$, and so by (3) and Theorem 1,

$$\begin{aligned}
\beta(n) &= 1 - \sum_{i=0}^{m} \binom{n}{s - i + ip} t^{i+(m-i)p} \\
&= 1 - \sum_{i=0}^{m} \binom{s}{i}\binom{m}{i} t^i \cdot t^{(m-i)p} \quad \text{by (4)} \\
&= 1 - \sum_{i=0}^{m} (-1)^i \binom{m}{i} t^i \cdot t^{(m-i)p} \\
&= 1 - (t^p - t)^m = 1 - \Gamma_n
\end{aligned}$$

by (3.1.1) of [**1**].

REFERENCES

[1] D. Goss, *Von staudt for $F_q[T]$*, Duke Math. J., **45** (1978), 885–910.
[2] ______, *Kummer and Herbrand criteria in the theory of function fields*, to appear.

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