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Structures of Human Relations and User-Dynamics Revealed by Traffic Data

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SUMMARY The number of customers of a service for Internet access from cellular phones in Japan has been explosively increasing for some time. We analyze the relation between the number of customers and the volume of traffic, with a view to finding clues to the structure of human relations among the very large set of potential customers of the service. The traffic data reveals that this structure is a scale-free network, and we calculate the exponent that governs the distribution of node degree in this network. The data also indicates that people who have many friends tend to subscribe to the service at an earlier stage. These results are useful for investigating various fields, including marketing strategies, the propagation of rumors, the spread of computer viruses, and so on.

key words: *i-mode, traffic, scale-free network, human relations, Zipf's law*

1. Introduction

The number of customers of NTT DoCoMo's 'i-mode service' in Japan (for Internet access from cellular phones) has been explosively increasing and recently reached about 40,000,000, although the service was only introduced five years ago [1]. Statistics on i-mode's growth thus provide an interesting body of information on the behavior of large numbers of users. Complex networks such as structures of social relations do not have an engineered architecture; rather, they are self-organized by the actions of large numbers of individuals. The local interactions can lead to the nontrivial global phenomenon of a scale-free distribution of node degree [2], which in turn leads to a small-world property [3], [4]. In this paper, we analyze the relation between the number of i-mode customers and the volume of traffic, with a view to finding clues to the structure of human relations among the very large set of potential i-mode customers. The traffic data reveals that this structure is a scale-free network, and we calculate the exponent that governs the distribution of node degree in this network. The data also indicates that people who have more friends tend to subscribe to the i-mode service at an earlier stage.

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If we consider each person as a node and each relation between two people as a link, we have a graphical model of human relations. If we can systematically characterize the structure of graphs thus derived, the characterization should be applicable to marketing strategies, the propagation of rumors and epidemic, and demand forecasting for telecommunications services, among others.

Networks of hyperlinks among web pages on the Internet and certain social networks have been reported to show small-world properties and act as scale-free networks. A scale-free network has a small number of 'hub' nodes, each of which has quite a lot of links. This feature acts to suppress increases in network diameter when the number of nodes increases. As a result, the average numbers of hops in the routes between all pairs of nodes are extremely small and information spreads with remarkable speed. The defining feature of a scale-free network is that the distribution of node degree obeys a power law, i.e. $n(k) \propto k^{-\gamma}$, where k and $n(k)$ denote the node degree (number of links) and the number of nodes of degree k, respectively, and γ is a positive constant. A wide variety of scale-free networks has been found, in both technological and social realms. In most cases, the relation $2.0 \le \gamma \le 3.4$ applies [5]. Ebel et al. [6] analyzed the logs of the e-mail server at Kiel University and produced a graph that represents the relationships among the e-mail accounts of the students. A link in the graph indicates the passage of at least one e-mail message between the corresponding pair of accounts. The graph in this case was a scale-free network with the slightly atypical γ value of 1.81. This result reflects human relations within a small community, in this case the set of people who use the university's e-mail server. The result is thus not applicable to people in general. Furthermore, since an e-mail log will almost certainly include records of multicast messages, i.e. messages sent to accounts on a mailing list, the passage of an e-mail message does not necessarily indicate a relationship between the owners of the corresponding pair of accounts, so the result does not solely reflect human relations. Abello et al. [7] and Aiello et al. [8] analyzed telephone calls on a certain day and produced a graph that represents the relationships among phone numbers. In this case, a link represents the setting up of a connection between the corresponding pair of numbers. This graph is a scale-free network with $\gamma = 2.1$. The data in this case is on a large number of non-specified people so the result should be generally applicable; however, a phone number often corresponds to a company or family rather than an individual, so the result does not reliably reflect human relations.

This paper is on our investigation of the relation between the number of i-mode customers and the volume of i-mode traffic. Simple analysis of this relation reveals some fundamental features of human relations for a large number of non-specified persons (the population within reach of the service). In addition, we clarify this population's dynamic behavior as a set of potential service subscribers.

The rest of this paper is organized as follows. In Sect. 2, we introduce our traffic data and point out the characteristics which make them desirable as a basis for analyzing human relations. In Sect. 3, we explain our assumptions and the framework of our investigation, and present the analytical and general form of the relation that characterizes i-mode e-mail usage. In Sects. 4–6, we assume various rules for the selection of new i-mode subscribers, and investigate the patterns of human relations they reflect and the user dynamics we would expect if the rule were correct. The rules are random distribution, identical and independent distributions, and a deterministic rule. Section 7 reveals that the structure of human relations forms a scale-free network. Finally, we conclude our discussion with Sect. 8.

2. Traffic Data

Data on i-mode service traffic is of particular interest for the following reasons.

- **(a)** The explosive growth of the service minimizes the effect on traffic of external factors such as changes in economic circumstances, family structure, and so on.
- **(b)** Since almost all cellular phone terminals are for personal use, the transfer of an e-mail message between two terminals unambiguously represents communication between the corresponding pair of customers.
- **(c)** Almost all e-mail traffic in the service is one to one, so we can assume proportionality between the volume of e-mail traffic and the number of customer pairs exchanging messages.
- **(d)** Sending an e-mail message is much cheaper than a voice communication, so external factors, e.g. the income of users, only have negligible effects on the traffic patterns.
- **(e)** In the early stages of popularization of the i-mode service, the combination of few e-mail advertisements and little sensationalism to attract nuisance users meant that very little of the traffic was independent of relationships among people.
- **(f)** The service was heavily advertised in the mass media. Information about the i-mode service was thus widely propagated within a short period and the intensity of the public campaign meant that propagation was independent of the topology of human relations.

The number of customers grew about three-fold, from 1,290,000 to 3,740,000, over the six months from Aug. 1999 to Jan. 2000 [1]. The relationship between the number of customers and the volume of i-mode web-service traffic in this period is shown in Fig. 1. Let the number of i-mode customers be m; the relationship is then written as

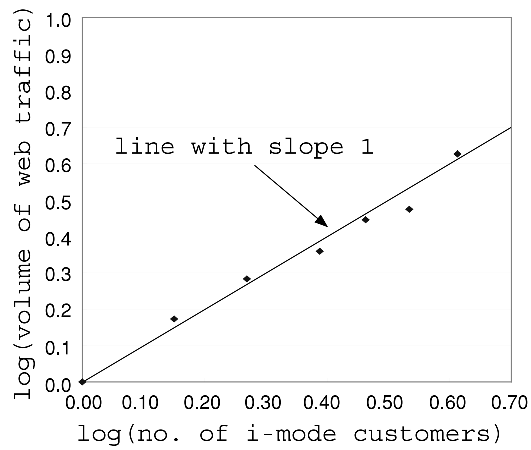

Fig. 1 A log-log plot of the number of i-mode customers versus the volume of web traffic (as the number of site-access operations). Traffic data is for August 1, 1999 to January 31, 2000. For both axes, the quantities are normalized on the result for August 1, 1999 as one. The line with slope one is for comparison.

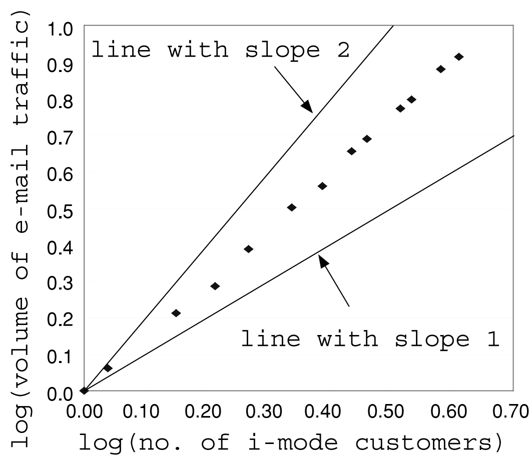

Fig. 2 A log-log plot of the number of i-mode customers versus the volume of e-mail traffic (as the number of messages sent). Traffic data is for August 1, 1999 to January 31, 2000. For both axes, the quantities are normalized on the August result as one. The lines are given for comparison.

$$\text{(i-mode web traffic)} \propto m. \tag{1}$$

The most reasonable explanation for this is a stable frequency of web access per user. The reason for this is as follows: if users who have subscribed to the i-mode service at an earlier stage are heavier users than more recent subscribers, the volume of web traffic will not be proportional to m. The result thus implies that the usage characteristics of the i-mode service for the average customer were stable over this period. The number of i-mode customers and the number of i-mode messages in the same period is given in Fig. 2. The data follows this power law:

$$\text{(i-mode e-mail traffic)} \propto m^{1.55}. \tag{2}$$

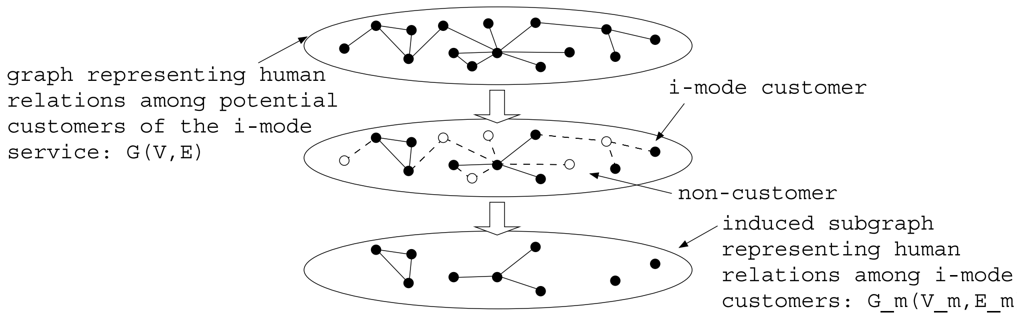

Fig. 3 The graph representing human relations, $G(V, E)$, and the subgraph $G_m(V_m, E_m)$ induced by i-mode customers.

Therefore, the number of e-mail messages increases more quickly than the volume of web traffic. If the number of e-mail messages for an average customer is independent of the number of i-mode customers and is stable, it should be proportional to m. A value greater than m reflects growth over time in the number of partners with whom the average customer might want to communicate. On the other hand, if the average customer knows a certain constant proportion of customers (even if this proportion is small, e.g. 0.0001%), the volume of e-mail traffic should be proportional to m^2. The fact that the volume of e-mail traffic is proportional to $m^{1+\alpha}$, where $0 < \alpha < 1$, means that while the number of possible communication partners increases, the ratio of this number to the number of all customers falls. The parameter $\alpha = 0.55$ characterizes the rate of growth for e-mail traffic. It also tells us something about the strength of human relations. Hereafter, we investigate the characteristics of human relations that satisfy Eq. (2).

3. Notation and Assumptions

Let the set of people in Japan (i.e. the set of all potential customers of the i-mode service) be V, and the set of pairs of people who exchange information with each other be E. The number of elements in V is $|V| = n$. We define human relations as a graph $G(V, E)$. We assume that $G(V, E)$ is stationary. Next, we use a rule to select m elements from V and let the subset of these selected elements be V_m ($m \leq n$). Let the subgraph induced by V_m from $G(V, E)$ be $G_m(V_m, E_m)$. That is, a node pair is connected by a link in $G_m(V_m, E_m)$ if and only if the corresponding node pair in $G(V, E)$ is connected by a link. Each element of V_m is an i-mode customer and human relations among all i-mode customers are represented by $G_m(V_m, E_m)$ (see Fig. 3). We assume that the number of links, $|E_m|$, in the induced subgraph $G_m(V_m, E_m)$ is proportional to the volume of e-mail traffic (as the number of messages) flowing in the i-mode service. Thus, to clarify the origin of the behavior that leads to Eq. (2), i.e. to $0 < \alpha < 1$, we need to find the condition of human relations $G(V, E)$, and not just of the subset of relations $G_m(V_m, E_m)$, that satisfies

$$|E_m| \propto m^{1+\alpha}. \tag{3}$$

In the following sections, we assume various possible rules for selection of subscribers to the i-mode service, identify the rule which corresponds with our data, that is, the rule which characterizes user-participation dynamics, and show the structure of human relations $G(V, E)$ thus implied.

4. Random Selection of New i-mode Customers

We sort all elements of V into descending order of degree (number of links connected to the element) with respect to the graph $G(V, E)$, and let the degree of the i-th element be D_i ($i = 1, 2, \ldots, n$). In cases where multiple nodes have the same degree, i is arbitrarily assigned. Similarly, all elements of V_m are sorted into descending order of degree with respect to the subgraph $G_m(V_m, E_m)$. We let the degree of the j-th element be d_j ($j = 1, 2, \ldots, m$).

Next, let us consider continuous versions of the degree distributions D_i and d_j, denoted by $D(x)$ and $d(y)$, respectively, where $0 \leq x \leq n$ and $0 \leq y \leq m$. The distribution $D(x)$ of degree is a monotonically decreasing function of x, and we choose $D(x)$ that satisfies

$$\sum_{i=a}^{b} D_i = \int_{a-1}^{b} D(x)\,\mathrm{d}x, \tag{4}$$

where arbitrary parameters a and b are integers which satisfy $1 \leq a \leq b \leq n$. We choose the distribution $d(y)$ in a similar way.

Since the elements of V_m are chosen from V, a node, which has the j-th largest degree, d_j ($j \in V_m$), in $G_m(V_m, E_m)$, will on average correspond to a node in the set with the i-th ($i = (n/m)\,j$) largest degree in $G(V, E)$. In addition, since the probability that the nodes connected to the node $i \in V$ in $G(V, E)$ are in V_m is $(m-1)/(n-1)$,

$$d_j \simeq \frac{m-1}{n-1} D_i, \tag{5}$$

on average. So, the expectation of the number of links in $G_m(V_m, E_m)$, that is, $F(m) := \mathrm{E}[|E_m|]$ are expressed as

$$\begin{aligned} F(m) &= \frac{1}{2} \sum_{j=1}^{m} d_j \\ &= \frac{1}{2} \int_{0}^{m} d(y)\,\mathrm{d}y \end{aligned}$$

$$\begin{aligned}
&\simeq \frac{1}{2}\,\frac{m-1}{n-1}\int_0^m D((n/m)y)\,\mathrm{d}y \\
&= \frac{1}{2}\,\frac{m-1}{n-1}\int_0^n D(x)\,\frac{\mathrm{d}y}{\mathrm{d}x}\,\mathrm{d}x \\
&= \frac{1}{2}\,\frac{m\,(m-1)}{n\,(n-1)}\int_0^n D(x)\,\mathrm{d}x \\
&= \frac{1}{2}\,\frac{m\,(m-1)}{n\,(n-1)}\sum_{i=1}^{n} D_i \qquad (6)\\
&= O(m^2). \qquad (7)
\end{aligned}$$

From the law of large numbers, we have $F(m) = |E_m|$ for $m \gg 1$. We therefore obtain

$$|E_m| = O(m^2). \qquad (8)$$

Consequently, if we assume that new customers of i-mode are selected at random, the volume of e-mail traffic is independent of the structure of human relations and increases by $O(m^2)$. This does not agree with Eq. (3).

5. Selection of New i-mode Customers according to Identical and Independent Distributions

In a similar way to the previous section, we sort all elements of V into descending order of degree, and let the degree of the i-th element be D_i $(i = 1, 2, \ldots, n)$. We assign the probability p_i $(i = 1, 2, \ldots, n)$ to all nodes $i \in V$ and select m nodes from V according to the probability p_i. We assume that node selection is according to an identical and independent distribution (i.i.d.), that is, it negligibly affects the probability distribution p_i. This assumption indicates that $m \ll n$ and requires $p_i \ll 1$ for all $i \in V$.

Let the set of m nodes selected from V be V_m, and the subgraph of $G(V, E)$ induced by V_m be $G_m(V_m, E_m)$. All elements of V_m are again sorted into descending order of degree in the subgraph $G_m(V_m, E_m)$; and let the degree of the j-th element be d_j $(j = 1, 2, \ldots, m)$.

As we did with the random-selection case, let us consider the continuous versions of the distributions of degree D_i and d_j as $D(x)$ and $d(y)$, and of probability p_i as $p(x)$, where $0 \le x \le n$ and $0 \le y \le m$. If $p_i > 0$ for all i $(i = 1, 2, \ldots, n)$, we can choose the density $p(x)$, which satisfies $p(x) > 0$ for arbitrary x $(0 \le x \le n)$ and

$$\sum_{i=a}^{b} p_i = \int_{a-1}^{b} p(x)\,\mathrm{d}x, \qquad (9)$$

where a and b are arbitrary integers that satisfy $1 \le a \le b \le n$.

Let us consider the distribution function that corresponds to the density function $p(x)$,

$$P(x) := \int_0^x p(s)\,\mathrm{d}s. \qquad (10)$$

Since $p(x) > 0$, there exists an inverse of the distribution function, $P^{-1}(u)$, for all $u \in [0, 1]$. Consider $\{x_1, x_2, \ldots, x_m\}$, which is a sequence of the points selected by probability density function $p(x)$ from $[0, 1]$ and sorted into ascending order. If we apply the distribution function P to transform the points $\{x_1, x_2, \ldots, x_m\}$, the points in $\{P(x_1), P(x_2), \ldots, P(x_m)\}$ are uniformly distributed on $[0, 1]$. So, the node corresponding to a node $j \in V_m$ is, on average, $x = P^{-1}(j/m)$. Therefore, we can express the relationship between $D(x)$ and $d(y)$ as

$$\int_0^m d(y)\,\mathrm{d}y \simeq c(m)\int_0^m D(P^{-1}(y/m))\,\mathrm{d}y, \qquad (11)$$

where $c(m)$ is a function of m. Incidentally, in the case in the previous section,

$$c(m) = \frac{m-1}{n-1}, \qquad (12)$$

and $p(x)$ is a constant.

Then, the expectation of the number of links in $G_m(V_m, E_m)$, $F(m) := \mathrm{E}\,[|E_m|]$ is expressed by

$$\begin{aligned}
F(m) &= \frac{1}{2}\sum_{j=1}^{m} d_j \\
&= \frac{1}{2}\int_0^m d(y)\,\mathrm{d}y \\
&\simeq \frac{1}{2}\,c(m)\int_0^m D(P^{-1}(y/m))\,\mathrm{d}y \\
&= \frac{1}{2}\,c(m)\int_0^n D(x)\,\frac{\mathrm{d}y}{\mathrm{d}x}\,\mathrm{d}x. \qquad (13)
\end{aligned}$$

Since $x = P^{-1}(y/m)$, we can obtain $\mathrm{d}y/\mathrm{d}x = m\,p(x)$. Thus,

$$F(m) = \frac{m}{2}\,c(m)\int_0^n D(x)\,p(x)\,\mathrm{d}x. \qquad (14)$$

If the probability density $p(x)$ is independent of the topology of the original graph $G(V, E)$, we can determine $c(m) = (m-1)/(n-1)$, and get

$$F(m) = \frac{1}{2}\,\frac{m\,(m-1)}{(n-1)}\sum_{i=1}^{n} D_i\,p_i. \qquad (15)$$

Comparison with Eq. (6) shows us that Eq. (15) is equivalent to selecting nodes at random for the graph with degree distribution $D'_i = n\,D_i\,p_i$. In particular, if nodes are selected at random, that is, $p(x) = 1/n$, Eq. (15) becomes identical with Eq. (6).

In popularization of the i-mode service, advertising in the mass media had far more power than did word of mouth. So, we can assume that the popularization process was independent of the topology of human relations. The number of subscribers among the average user's friends and acquaintances is thus proportional to the number of i-mode subscribers, so we can state that

$$c(m) \propto m. \qquad (16)$$

Thus, we have

$$F(m) \simeq O(m^2) \times \int_0^n D(x)\, p(x)\, \mathrm{d}x. \tag{17}$$

Since, in order to realize $|V_m| = O(m^{1+\alpha})$, $F(m)$ has to satisfy $F(m) = O(m^{1+\alpha})$. So, we have

$$\int_0^n D(x)\, p(x)\, \mathrm{d}x = O(m^{\alpha-1}), \tag{18}$$

or in discrete form,

$$\sum_{i=1}^{n} D_i\, p_i = O(m^{\alpha-1}). \tag{19}$$

Since $D(x)$ and D_i are independent of m, Eqs. (18) and (19) mean that $p(x)$ and p_i depend on m. This result contradicts the assumption of i.i.d.

6. The Structure of Human Relations and the Rule for Subscription to the i-mode Service

The previous section demonstrated that the probability of selecting a given node changes after each node selection. Since setting a new probability for every node selection is complex, we adopt a deterministic approach.

We sort all elements of V into descending order of degree (number of links connected to the element), and let the degree of the i-th element be D_i ($i = 1, 2, \ldots, n$). In cases where multiple nodes have the same degree, i is arbitrarily assigned. Similarly, all elements of V_m are sorted into descending order of degree in the subgraph $G_m(V_m, E_m)$. We let the degree of the j-th element be d_j ($j = 1, 2, \ldots, m$).

On the other hand, we sort those elements of V that have been selected for V_m into their order of selection, and let the degree within V of the k-th element be $D_k^{(s)}$ ($k = 1, 2, \ldots, n$). All elements of V_m are sorted into the same order. Let the degree within V_m of the h-th element be $d_h^{(s)}$ ($h = 1, 2, \ldots, m$). While the g-th element, $g \in V_m$, corresponds to $g \in V$, $d_g^{(s)}$ is very rarely the same as $D_g^{(s)}$.

If we select m elements from V, the degree within $G_m(V_m, E_m)$ of the selected elements can be written as

$$\sum_{k=1}^{m} d_k^{(s)} \simeq c(m) \sum_{k=1}^{m} D_k^{(s)}, \tag{20}$$

where $c(m)$ is a function of m. The number of links in $G_m(V_m, E_m)$ is then written as

$$\begin{aligned} |E_m| &= \frac{1}{2} \sum_{k=1}^{m} d_k^{(s)} \\ &\simeq \frac{1}{2} c(m) \sum_{k=1}^{m} D_k^{(s)}. \end{aligned} \tag{21}$$

As was earlier stated, advertising in the mass media had far more power as a popularizer of the i-mode service than did word of mouth, from which we obtained Eq. (16). Then, from Eq. (3), we have

$$\sum_{k=1}^{m} D_k^{(s)} \propto m^{\alpha}. \tag{22}$$

Since Eq. (22) is valid for all m, we have

$$D_k^{(s)} \propto k^{\alpha-1}. \tag{23}$$

The above results are rephrased below.

- (Result A) The elements of V_m tend to be selected from V in descending order of degree in $G(V, E)$. In other words, a person who has many friends tends to subscribe to the i-mode service at an earlier stage.
- (Result B) The distribution of degree among the elements of V obeys Zipf's law [9]. That is, for the degree D_i of the i-th element of V (the indices are determined in descending order of degree)

  $$D_i \propto i^{-\beta} \tag{24}$$

  holds, where $\beta > 0$ is a constant and $\beta = 1 - \alpha$.

Conversely, Results A and B along with $c(m) \propto m$ lead us to Eq. (3).

7. The Structure of Human Relations as a Scale-Free Network

We consider the distribution of degree, $n(k)$, for a $G(V, E)$ the elements of which satisfy Result B. Let the slope of Zipf's law in the log-log plane be $-\beta$. We consider the degree of the x-th element, $Z(x)$. For constants $a > 0$ and $c_1 > 0$, the degrees of the x-th and ax-th elements are written as

$$Z(x) = \frac{c_1}{x^{\beta}}, \quad \text{and} \tag{25}$$

$$Z(ax) = \frac{c_1}{(ax)^{\beta}}. \tag{26}$$

Since the slopes at both $(x, Z(x))$ and $(ax, Z(ax))$ are $-\beta$ on a log-log scale, let us consider two triangles which are congruent in the log-log plane (see Fig. 4). The lengths of the bases of the two triangles are related to $n(Z(x))$ and $n(Z(ax))$. More specifically, the ratio of the two lengths in the linear plane is equal to $n(Z(x)) : n(Z(ax))$. Thus, we have $n(Z(x)) : n(Z(ax)) = 1 : a$. Consequently, for a constant $c_2 > 0$,

$$n(Z(x)) = c_2, \quad \text{and} \tag{27}$$

$$n(Z(ax)) = c_2\, a. \tag{28}$$

We can plot the points $(Z(x), n(Z(x)))$ and $(Z(ax), n(Z(ax)))$ and then derive the slope of the line connecting the two points on the log-log plane as

$$\gamma = \frac{\log n(Z(ax)) - \log n(Z(x))}{\log Z(x) - \log Z(ax)} \frac{1}{\beta}. \tag{29}$$

The above equation, Eq. (29), is independent of a. Thus, the distribution of degree is obtained as

$$n(k) \propto k^{-\gamma}, \tag{30}$$

where $\gamma = 1/\beta$. This relation is called Lotka's law [9]; since

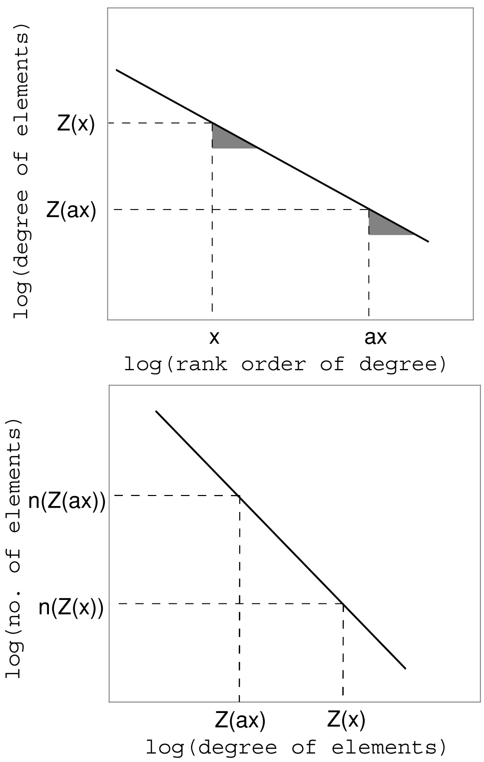

Fig. 4 Two points extracted from data that satisfies Zipf's law (upper panel) and plotted on a Lotka-type graph (lower panel).

it is a consequence of Zipf's law, the two laws accompany each other (e.g. in Internet access [10]). From the above discussion and Result B, we get the following result:

- (Result C) The graph that represents human relations is a scale-free network, with distribution of degree described by Eq. (30) and

$$\gamma = \frac{1}{1-\alpha}. \tag{31}$$

By using the experimental value $\alpha = 0.55$, we get

$$n(k) \propto k^{-2.22}. \tag{32}$$

8. Concluding Remarks

Results A–C were derived on the assumption that $c(m) \propto m$, where m is the number of subscribers and $c(m)$ is, for the average user, the ratio of the number of friends who are subscribers to the i-mode service to his/her total number of friends. This is based on the assumption that the process of popularization is independent of the topology of human relations, which is in turn based on the fact that advertisements for i-mode in the mass media have been very much more powerful as popularizers of the service than the diffusion of information by word of mouth. However, in cases where the diffusion of information by word of mouth plays a non-negligible role, $c(m) \neq O(m)$. Our purpose in this paper has been to describe the characteristics of human relations revealed by data on the i-mode service. Results B and C are valid as descriptions of human relations and both will be useful for investigating other fields including marketing strategies, the propagation of rumors, and the spread of epidemics.

In addition to information on the structure of human relations, we also obtained Result A, which concerns the dynamic behavior of customers. This result is applicable as a description of how a money spinner emerges. We expect that combining knowledge of the three results will lead to efficient marketing strategies.

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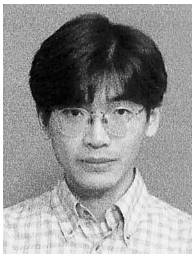

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