Self-adjusting routing schemes for time-varying traffic in scale-free networks

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We consider the effects of time-varying packet generation rates in the performance of communication networks. The time variations could be a result of the patterns in human activities. As a model, we study the effects of a degree-dependent packet generation rate that includes a sinusoidal term. Applying a modified traffic awareness protocol (TAP) previously proposed for static packet generation rates to the present situation leads to an altered value of the optimization parameter, when compared to that obtained in the static case. To enhance the performance and to cope with the time-varying effects better, we propose a class of self-adjusting traffic awareness protocols that makes use of instantaneous traffic information beyond that included in the modified TAP. Two special cases that make use of global and local information, respectively, are studied. Comparing results of our proposal schemes with the modified TAP, it is shown that the present self-adjusting schemes perform more effectively.

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I. INTRODUCTION

The study of transport processes on networks is fundamental to a large part of the physical, biological, social, economic, and engineering sciences and has recently received a great attention, such as the traffic of information packets, synchronization, epidemic spreading, particle condensation, etc. [1,2]. It is found that the optimal performance of transports depends strongly on both the structural characteristics of the underlying network and routing algorithm of traffic. For example, the clustering, disassortativity, and modularity of scale-free network may influence significantly the statistical properties of traffic [3,4]. Based on the fact that most of the realistic networks are of scale-free architecture, we here focus on the communication networks with scale-free topology such as the famous Barabasi-Albert (BA) network with exponent of degree distribution $\gamma=3$ [5]. The motivation to choose BA network is to show a general consideration but not only limit to some specific networks, and also hope the results can help us to understand the traffic in the Internet with exponent of degree distribution $\gamma=2.2\pm 0.1$ [6,7].

There are two general ways to enhance the performance of a network: To increase the capacity of each node and to improve the routing protocol. The former is less practical as there is usually no central management to plan and organize the network, such as the Internet. Thus, much effort has been focused on improving the routing protocol [8–29]. The simplest routing algorithm is to follow the geometrical shortest path where packets are sent via the path with the minimum number of intermediate nodes from the source to the destination. For networks with a power-law degree distribution, there exist nodes with large betweenness [8]. When the traffic is heavy, many packets will have to pass through these hubs on their way to the destination and lead to a traffic jam when the packets queue up at the hubs due to the finite capacity of the hubs in handling packets. One obvious way to enhance the performance is to focus on reducing the jam at the hubs. For example, congestions can be largely suppressed by selectively improving the capacity of only 3% of nodes of heavy links in a network [21].

To avoid congestions, many variations in the shortest path routing protocol have been proposed. Typically, they take the time of queuing at the nodes into consideration. In a communication network, the nodes serve as both hosts and routers, and the links are pathways through which packets are delivered. In early models of traffic in communication networks, every node is assumed to have the same packet delivery rate of handling one packet per time step and R new packets are generated randomly among the nodes in the system [8–20]. The purpose of these models is to enhance the congestion threshold R_c in scale-free networks. For example, Yan *et al.* presented an approach to include the link weight [9]. Wang *et al.* proposed a routing strategy with a tunable parameter α based on the local structural information [10]. Sreenivasan *et al.* derived an estimate to the upper bound of the congestion threshold for scale-free networks and introduce a hub avoidance protocol for large packet insertion rate [11]. Danila *et al.* gave a heuristic algorithm that balances traffic on a network by minimizing the maximum node betweenness [14,15]. Also Kujawski *et al.* introduced some algorithms based on dynamical information, which can handle a larger load than the random-walk algorithm [16].

The traffic awareness protocol (TAP) proposed by Echenique *et al.* [18,19] forms the basis of some variations [20]. In TAP, a node i decides to forward a packet to a neighboring node ℓ with the shortest *effective* distance $hd_{\ell,j}+(1-h)n_\ell$ toward the destination j, where $d_{\ell,j}$ is the length of the shortest path from node ℓ to j, n_ℓ is the number of accumulated packets at node ℓ and it is in general time-dependent, and h is a traffic awareness parameter. It was found that $h\approx 0.8$ gives the best performance [18,19]. TAP thus considers a balance between routing via the geometrical shortest path (first term) and the waiting time at the nearest-neighboring nodes ℓ of i (second term). In the free-flow phase of traffic where packets travel freely without delays, the shortest path algorithm will be adopted under TAP. In the heavily con-

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gested phase, e.g., at high packet generation rates, packets accumulate in the system and the number of packets in the system increases linearly with time. Under heavy congestions, no routing protocol would work. TAP and other modified routing protocols improve the performance in situations when the shortest path algorithm alone starts to lead to accumulated queues of packets, especially at the hubs. Using TAP, it is possible to maintain traffic flow at generation rates that the system would have been jammed under the shortest path algorithm by delivering packets through longer paths, i.e., avoiding the hubs when they carry long queues. Obviously, there will be more packets in the whole system under TAP in the steady state.

The autonomous nature in communication networks implies that the nodes are heterogeneous, with degree-dependent packet generation and delivering rates. Systems with packet generation rate of the form λk_i [21–23] and delivering rate $(1+\beta k_i)$ [24,25] have been proposed and studied. Here, k_i is the degree of node i, and λ and β are constants. In this case, a better performing routing algorithm refers to one that can keep the traffic flowing at a higher packet generation rate characterized by λ for given and fixed value of β, or equivalently, for a fixed value of λ using a lower delivering capacity characterized by β. For degree-dependent delivering capacities, a modified TAP is to forward a packet from a node i to a neighboring node ℓ with the smallest value of an effective distance [22] denoted by

$$d_{eff}^{\ell} = hd_{\ell,j} + (1-h)\frac{n_\ell}{1+\beta k_\ell}, \tag{1}$$

where $n_\ell/(1+\beta k_\ell)$ is the waiting time for a new packet to leave the node ℓ.

Except the above routing policies, message transferring on other types of networks such as two-dimensional (2D) networks, WWW network [30], and sparse modular networks [31] has been also studied. For 2D networks, Singh *et al.* found that the gradient mechanism applied to hubs of high betweenness centrality is an extremely efficient way of relieving congestion [26,27]. Li *et al.* developed a weight assignment scheme to lower the maximum effective betweenness centrality of 2D small-world network [28]. For the WWW network, Tadić *et al.* investigated the traffic dynamics based on local information and found the relationship between global statistical properties and temporal fluctuations [3,29]. For the sparse modular network, Tadić *et al.* found that the network composed of several modules with clustered scale-free structure can bear much larger traffic density, compared to the network of the same size but with a single module of the same structure [4].

In the present work, we consider the effects of the time-varying nature of human activities. For example, during a day, there are busy hours when more people are using the Internet for business or communications. Similarly, there are also busier days in a week, e.g., the traffic will be different for weekdays and weekends [32]. On a longer time scale, there are many more mails sent during the holiday season and the new year time. Previous studies ignored the time-dependent feature of the packet generation rate. Here, as a simple model that incorporates explicit time-varying features, we consider a degree-dependent packet generation rate that is sinusoidal about a mean. To cope with the time-varying effects, we propose a class of self-adjusted traffic awareness protocols that makes use of instantaneous traffic information beyond that included in n_ℓ in Eq. (1). We studied two special cases of our proposal that make use of global and local information, respectively. We compare results of our proposals with TAP and show that the proposed routing algorithms perform more effectively.

The paper is organized as follows. In Sec. II, we introduce the time-varying packet generation rate and study the performance of a modified TAP. To improve the performance and being motivated by TAP, we present our routing algorithm and focus our discussion on two special cases: The global self-adjusting traffic awareness protocol (GSA-TAP) and local self-adjusting traffic awareness protocol (LSA-TAP). In Sec. III, we determine the optimal conditions for the two protocols and compare the performance of these protocols with the modified TAP. We found that our proposed protocols are more efficient. In Sec. IV, we study the statistical properties of traffic and compare the differences caused by the routing approaches. These results provide more evidence to show the efficiency of our approaches. We summarize and discuss our findings in Sec. V.

II. ROUTING ALGORITHMS

For concreteness, we study traffic in the BA network consisting of $N=1000$ nodes. Starting with $m=3$ initial nodes, one new node is introduced every time step and each new node is allowed to establish m new links with the existing nodes according to the preferential attachment scheme, i.e., the probability of establishing a new link to a node i is proportional to the degree k_i. The process is repeated until the desired network size is achieved [5,33]. The resulting network has an average degree $\langle k\rangle=2m=6$ and a power-law degree distribution $P(k)\sim k^{-3}$ for large networks.

To study the time-varying effects such as rush hours and/or busy seasons, we generalize the degree-dependent packet generation rate λk_i in previous works [21–23] to incorporate a sinusoidal behavior. The packet generation rate of a node i with degree k_i is assumed to take on the form

$$\lambda(t,k_i) = \lambda_0 k_i + k_i A \sin \omega t, \tag{2}$$

where $A \sin \omega t$ represents the periodic changes between the rush hours and the normal time. Here, A is the amplitude of the periodic changes and ω is the frequency. The values A and ω reflect how the people in a country or region behave. The parameter λ_0 plays the role of λ in previous studies on static packet generation rates.

At each time step, packets are generated based on $\lambda(t,k_i)$. Each new packet queues up at the node at which the packet is generated and it is assigned a destination randomly. We also assume a packet delivery rate that is proportional to the degree of a node. At each time step, a node i delivers at most $(1+\beta k_i)$ packets to its neighbors, with the fractional part of $(1+\beta k_i)$ implemented probabilistically [21–25]. The delivery of packets will be made on a First-In-First-Out policy. A packet arriving at a node is put at the end of the queue there.

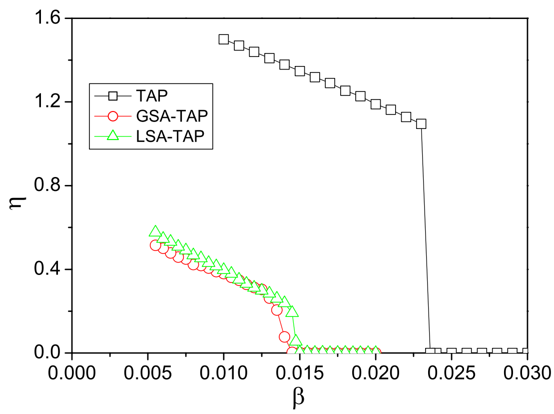

FIG. 1. (Color online) The quantity η versus the delivering parameter β for BA network with $N=1000$, $\lambda_0=0.01$, $A=0.005$, $\omega=0.01$, where the "squares" denote the case of TAP with $h=0.8$, the "circles" denote the case of GSA-TAP with the effective parameter $Q=2.5$ [will be defined later in Eq. (6)], and the "triangles" denote the case of LSA-TAP with effective parameter $Q'=1.0$ [will be defined later in Eq. (8)].

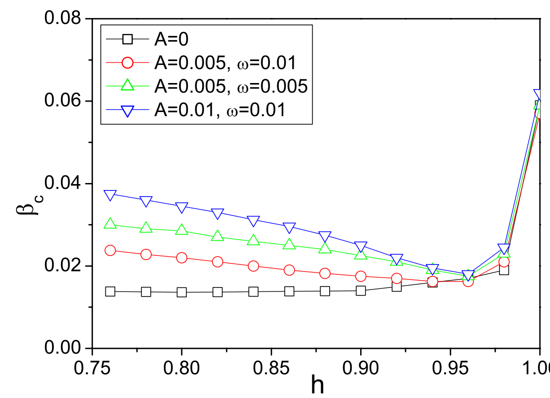

FIG. 2. (Color online) Values of β_c in the packet delivery capacity for smooth traffic as a function of the traffic awareness parameter h in the modified TAP given by Eq. (1), for different values of A and ω in the packet generation rate specified by Eq. (2) and $N=1000$, $\lambda_0=0.01$. Results for $A=0$ (squares), $A=0.005$ and $\omega=0.01$ (circles), $A=0.005$ and $\omega=0.005$ (triangles), and $A=0.01$ and $\omega=0.01$ (inverted triangles) are shown.

The packets are routed to their destinations based on some routing algorithms and are considered as removed once arriving their destinations. The generation of new packets and the routing of packets are carried out simultaneously on the nodes in a time step.

A larger value of β implies every node has a higher capacity in handling packets. Given a set of parameters λ_0, A, and ω, there exists a critical value β_c below which the system is in the congested phase. A way to obtain β_c is to look at how the average number of packets $\langle n(t)\rangle$ at a node changes with time. Let $S(t)$ be the total number of packets in the network at time t and $\eta\equiv\langle\frac{dn(t)}{dt}\rangle$ be the slope of $n(t)$ in the long time limit. We have

$$\eta=\frac{1}{2mN\lambda_0}\lim_{t\to\infty}\frac{\langle S(t+\Delta t)-S(t)\rangle}{\Delta t}, \tag{3}$$

where the normalization factor $2mN\lambda_0$ is the total packets produced at each time step. When the system is in the congested phase, $\eta>0$. The critical value β_c is the value of β that separates the $\eta=0$ and $\eta>0$ behavior. For identical packet generation and delivery rates, two routing algorithms would give different values of β_c and the one with the lower β_c is the more effective algorithm. Figure 1 shows the relationship between η and β for three different approaches where the "squares" denote the case of TAP with $h=0.8$ and the "circles" and "triangles" denote the cases of GSA-TAP and LSA-TAP in Eqs. (6) and (8) (which will be defined later), respectively. Obviously, their β_c are different and the GSA-TAP has the smallest β_c, indicating the GSA-TAP is the most effective approach of the three.

The routing policy plays the crucial role in setting the rules of how a packet is forwarded toward its destination. With the packet generation rate in Eq. (2), we explore different routing protocols. For a node i, the modified TAP in Eq. (1) forward packet to a neighboring node ℓ with the smallest value of d_{eff}^{ℓ}, which considers both the geometrically shortest path toward the destination and the waiting time at the node ℓ [18]. For $A=0$, the effective performance value $h\approx0.8$ to 0.85 gives the best performance [18,22]. Note that $n_\ell(t)$ in Eq. (1) is time dependent even for $A=0$. For $A\neq0$, the time dependence of $n_\ell(t)$ comes from both the probabilistic implementations of the packet generation and delivery rates *and* the sinusoidal term in Eq. (2). Thus, applying the modified TAP to the present situation is the simplest approach and it makes use of only single-node information at the neighboring nodes ℓ of node i and a single time-independent parameter h for routing.

The parameter h in the modified TAP can be tuned to give the best performance. Figure 2 shows the results of β_c as a function of the parameter h, for different values of A and ω in packet generation with a fixed $\lambda_0=0.01$. The results for $A=0$ show a maximum capacity with a minimum β_c in the range $h\in[0.76,0.88]$, which is consistent with previous results [18,22]. For cases with $A\neq0$, the results indicate that a minimum β_c is attained at the value of $h\approx0.96$, and the values of β_c for $A\neq0$ is higher than that of $A=0$. The value $h\approx0.96$ implies that the routing strategy is closer to the shortest path protocol. For the duration in which the second term in Eq. (2) is negative (positive), there are fewer (more) packets generated and thus the shortest path protocol (TAP) with $h=1$ ($h\approx0.8$) would be advantageous in this portion of a period. Fewer packets in part of a period lead to a value of h closer to unity.

To better cope with the time variations that emerge from both the probabilistic implementations of packet generation and delivery and the time-dependent packet generation rate [Eq. (2)], a natural extension of the modified TAP in Eq. (1) is to introduce a time-dependent traffic awareness parameter $h(t)$. However, this would make TAP more complicated and harder to implement, and thus less useful. If we were to impose $h(t)$ into Eq. (1), then there would be a factor $h(t)/1-h(t)$ in the first term of the quantity $d_{eff}^{\ell}/[1-h(t)]$. Given that $n_\ell(t)$ incorporates only the information of the queue length at the node ℓ, the time-dependent factor $h(t)/[1-h(t)]$ can be taken to reflect the instantaneous status of the traffic in the system, due to the time-dependent term in packet generations and based on information away from the node ℓ. We are thus motivated to propose a class of self-adjusting traffic awareness protocols (SA-TAPs) in which a node i would forward a packet to a nearest-neighboring node ℓ with the smallest value of D^{ℓ}_{eff} given by the form

$$D^{\ell}_{eff} = \bar{Q}\mathcal{N}(t)d_{\ell,j} + \frac{n_\ell(t)}{1+\beta k_\ell}, \tag{4}$$

where $\mathcal{N}(t)$ is an quantity that characterizes the instantaneous traffic and carries information more than the queue length at node ℓ, and $\bar{Q}$ is a time-independent parameter that can be tuned to optimize traffic. Note that D^{ℓ}_{eff} is different from d^{ℓ}_{eff} in Eq. (1).

Here, we consider two different forms of $\mathcal{N}(t)$. Due to the $A \sin \omega t$ term in Eq. (2), the total number of packets will carry a time dependence that is otherwise absent for $A=0$. Thus, a choice of $\mathcal{N}(t)$ is the instantaneous number of packets per node in the system $\langle n(t)\rangle$ given by

$$\langle n(t)\rangle = \frac{1}{N}\sum_{i=1}^{N} n_i(t). \tag{5}$$

This choice requires knowing the number of packets in the system, which is global information. We term this the GSA-TAP. Routing using GSA-TAP is thus based on the consideration of

$$D^{\ell}_{G,eff} = Q\langle n(t)\rangle d_{\ell,j} + \frac{n_\ell(t)}{1+\beta k_\ell}, \tag{6}$$

where we represented the time-independent parameter by Q. Another choice of $\mathcal{N}(t)$ is to include only the information in the vicinity of the node ℓ up to its next-nearest neighbors. We define $\langle n_{\ell,2}(t)\rangle$ for a node ℓ as

$$\langle n_{\ell,2}(t)\rangle = \frac{1}{a}\sum_{i\in\{nn+nnn,\ell\}} n_i(t), \tag{7}$$

where the sum is over all the nearest-neighboring and next-nearest-neighboring nodes of node ℓ and the normalization factor a is the number of nodes included in the summation. This choice requires knowing the queue lengths in the neighborhood of node ℓ, which is a local information. We term this the LSA-TAP. Routing using LSA-TAP is thus based on the consideration of

$$D^{\ell}_{L,eff} = Q'\langle n_{\ell,2}(t)\rangle d_{\ell,j} + \frac{n_\ell(t)}{1+\beta k_\ell}, \tag{8}$$

where we represented the time-independent parameter by Q'. It should be noted that in extreme case one packet walks to its destination, the packet would be delivered along the shortest path because the second term in Eq. (8) is zero and the coefficient of the first term is a constant, i.e., $\langle n_{\ell,2}(t)\rangle = const$.

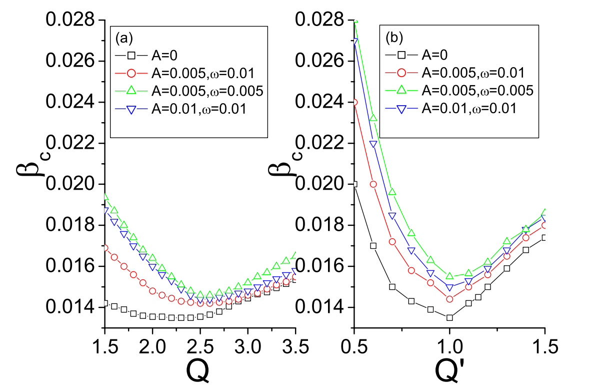

FIG. 3. (Color online) Values of β_c in the packet delivery capacity for smooth traffic versus (a) the traffic awareness parameter Q in GSA-TAP given by Eq. (6), and (b) the traffic awareness parameter Q' in LSA-TAP given by Eq. (8), for different values of A and ω in the packet generation rate specified by Eq. (2) with $N=1000$ and $\lambda_0=0.01$. Results for $A=0$ (squares), $A=0.005$ and $\omega=0.01$ (circles), $A=0.005$ and $\omega=0.005$ (triangles), and $A=0.01$ and $\omega=0.01$ (inverted triangles) are shown.

III. EFFECTIVE PERFORMANCE OF GSA-TAP AND LSA-TAP

To establish the usefulness of GSA-TAP and LSA-TAP, we apply the algorithms to the cases studied in Fig. 2 and look for the effective values of Q and Q'. Figure 3 shows the results of how the values of β_c depend on the time-independent parameters Q in GSA-TAP and Q' in LSA-TAP. With the time-dependent packet generation rate Eq. (2), GSA-TAP and LSA-TAP give minimum values of β_c at $Q\approx 2.5$ and $Q'\approx 1.0$ for the different cases with $A\neq 0$, respectively, and the minimum values for $A\neq 0$ are higher than that for $A=0$. For identical packet generation rate, the minimum values of β_c obtained by GSA-TAP is a little lower than that of LSA-TAP, indicating that the network capacity of global information is slightly better than that of local information. Our further numerical simulations show that this result works for different network sizes, see Fig. 4 for three other typical cases of $N=500$, 2000, and 4000 where the left and right panels represent the GSA-TAP and LSA-TAP, respectively. From Fig. 4 it is easy to see that the effective $Q\approx 2.5$ and $Q'\approx 1.0$ do not change for different network sizes. For later comparisons with the modified TAP, we will use $Q=2.5$ for GSA-TAP and $Q'=1.0$ for LSA-TAP.

To compare the performances of different routing schemes, we compare the values of β_c using the modified TAP [Eq. (1)] with the optimal parameter $h=0.96$, GSA-TAP with $Q=2.5$ and LSA-TAP with $Q'=1.0$, under identical packet generation rates given by Eq. (2). Recall that a smaller value of β_c implies less resources for packet delivery and thus represents a better performance. As there are three parameters λ_0, A, and ω in Eq. (2), we show the results of β_c versus one of these parameters, when the other two are kept fixed in Fig. 5. We also include the results for the modified TAP with $h=0.8$, which is an effective parameter for the case of $A=0$, for comparison. Obviously, the performance of the modified TAP with $h=0.8$ is worse than the other three routing schemes in all the cases considered.

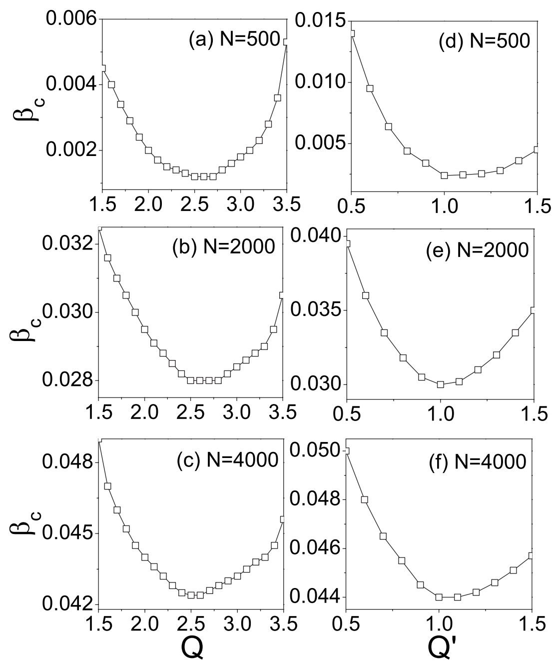

FIG. 4. How β_c changes for different network sizes where the left and right panels represent the GSA-TAP and LSA-TAP, respectively. The parameters are $\lambda_0=0.01$, $A=0.005$ and $\omega=0.01$, and (a) and (d) denote the case of $N=500$, (b) and (e) the case of $N=2000$, and (c) and (f) the case of $N=4000$.

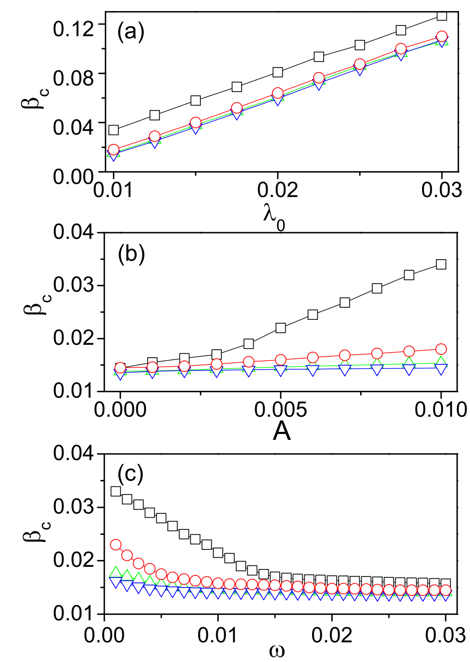

FIG. 5. (Color online) Comparison among values of β_c in the packet delivery capacity for smooth traffic using different traffic awareness protocols versus the parameters in the packet generation rate given by Eq. (2) with $N=1000$. (a) β_c versus λ_0, with $A=0.005$ and $\omega=0.01$; (b) β_c versus A, with $\lambda_0=0.01$ and $\omega=0.01$; and (c) β_c versus ω, for $\lambda_0=0.01$ and $A=0.005$. Results for the modified TAP with $h=0.96$ (circles), GSA-TAP with $Q=2.5$ (triangles), and LSA-TAP with $Q'=1.0$ (inverted triangles) are shown. Results for the modified TAP with $h=0.8$ (squares), which is proposed for the case of $A=0$, are also included for comparison.

Figure 5(a) shows the results for β_c against λ_0, with $A=0.005$ and $\omega=0.01$. Over the range of λ_0 studied, the three versions of TAPs give similar results. The GSA-TAP and LSA-TAP give a slightly smaller β_c than the modified TAP with $h=0.96$, thus showing the advantage of using SA-TAPs. The edge of GSA-TAP and LSA-TAP over the modified TAP is seen more clearly in Fig. 5(b), where the amplitude A is varied with $\lambda_0=0.01$ and $\omega=0.01$ kept fixed. Note that the values of β_c for GSA-TAP and LSA-TAP do not change much with A, while β_c for the modified TAP increases with A. Thus, the SA-TAPs could maintain smooth traffic for different amplitudes in packet generation using nearly the same value of β. For higher values of A, LSA-TAP gives a slightly lower value of β_c than GSA-TAP. Thus, ensuring step by step that a packet is forwarded to a neighboring node that would further forward the packet quicker as in LSA-TAP is more important.

Figure 5(c) shows the results as a function of ω, for fixed $\lambda_0=0.01$ and $A=0.005$. For small ω ($\omega<0.15$), SA-TAPs outperforms the modified TAP. For modified TAP (with $h=0.96$ and $h=0.8$), the values of β_c drop with ω rapidly, while β_c only drops slightly with ω for GSA-TAP and LSA-TAP. As ω increases, the values of β_c for the different versions of TAPs tend to merge, and even the modified TAP with $h=0.8$ gives similar performance. This is understandable in that when ω is large, the corresponding period in the time variation is short. When the period of oscillating packet generation is much shorter than the average time that it takes for a packet to reach its destination, the oscillatory packet generations simply imply more packets are generated in these few time steps and less packets are generated a few time steps later. During this cycle, the packets are only on their way to the destinations. In this case, the effect of the oscillating term in Eq. (2) diminishes after time averaging. The packet generation rate is dominated by the first term and thus the parameter λ_0, as in the cases of static packet generations. This leads to the similar performance among the TAPs. Over the range of ω studied, GSA-TAP and LSA-TAP still perform slightly better.

IV. STATISTICAL PROPERTIES OF TRAFFIC

Except the measure of the delivering capacity β_c, the efficiency of routing strategy can be also characterized by other statistical quantities such as the distributions of queue lengths, waiting times, and travel times, the average number of packets in network, and the average travel time, etc. [3,4,29,34,35]. An effective routing approach should have the smallest β_c and minimize these statistical quantities. In this section, we will use them to further illustrate the efficiency of the SA-TAPs.

Generally, packets form queues when two or more packets are at same node at the same time. Packets queue dynamically at nodes because of the stochastic feature of transport process. The accumulated packets at a node, n_ℓ, is the queue length. All the queue lengths of the N nodes will form a distribution $P(n)$. Although each individual n_ℓ is time dependent, $P(n)$ may not change with time and thus can be used to

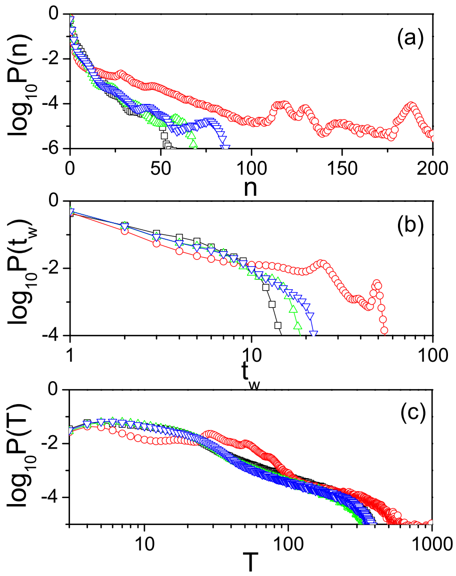

FIG. 6. (Color online) Global transport characteristics from a computation time window of 10^4 time steps. (a) Distribution of queue lengths $P(n)$ versus n; (b) Distribution of waiting times $P(t_w)$ versus t_w; (c) Distribution of travel times $P(T)$ versus T. The parameters are $\beta=0.024$, $N=1000$, $\lambda_0=0.01$, $A=0.005$, and $\omega=0.01$, and the "squares," "circles," "triangles," and "inverted triangles" represent the cases of TAP with $h=0.8$, $h=0.96$, GSA-TAP with $Q=2.5$, and LSA-TAP with $Q'=1.0$, respectively.

reflect the network structure and the efficiency of routing approach in a particular way [3]. When the queue length is long, the later coming packets will wait there for a long time before it is delivered out. The waiting time $t_w(i)$ is defined as the time for a packet to spend in a particular node $-i$ waiting to leave. It depends not only on the queue length but also on the delivering ability of that node, i.e., $1+\beta k_i$. When there is no congestion, the waiting times are $t_w=1$ for all the nodes. For a specific packet, the sum of all its waiting time along the path from its creation to its delivery at its destination is called the travel time and can be calculated by

$$T = \sum_{i \in \text{the path}} t_w(i). \tag{9}$$

The travel time of a packet is related to its travel costs [3]. Same to the queue length, both the waiting time t_w and the travel time T are of some stochastic feature but their distribution may be invariant. Therefore, we are here interesting in the distributions of queue lengths, waiting times, and travel times.

In numerical simulations, we calculate the distributions of queue lengths, waiting times, and travel times in a time window of $\Delta t=10^4$. For comparison, we would like to choose a common β for both the SA-TAPs and the modified TAP and let all the considered cases be not in the congested state. As the modified TAP with $h=0.8$ has the largest $\beta_c=0.024$ in the considered cases, we here choose $\beta=\beta_c=0.024$ in our numerical simulations. Figure 6 shows the results for parameters $N=1000$, $\lambda_0=0.01$, $A=0.005$, and $\omega=0.01$, where (a) represents the distribution of queue lengths, (b) the distribution of waiting times, (c) the distribution of travel times, and

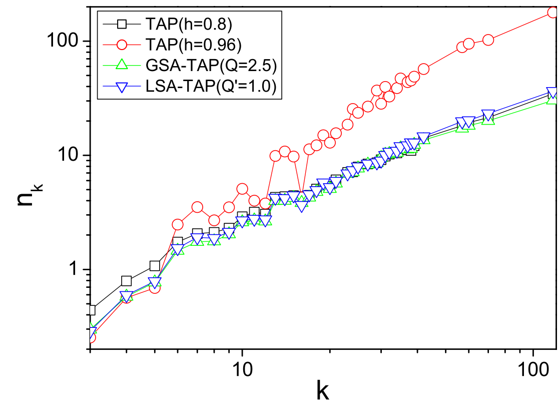

FIG. 7. (Color online) The average packets n_k versus k for parameters $\beta=0.024$, $N=1000$, $\lambda_0=0.01$, $A=0.005$ and $\omega=0.01$, where the "squares," "circles," "triangles, " and "inverted triangles" represent the cases of TAP with $h=0.8$, $h=0.96$, GSA-TAP with $Q=2.5$, and LSA-TAP with $Q'=1.0$, respectively.

the "squares," "circles," "triangles," and "inverted triangles" represent the cases of TAP with $h=0.8$, $h=0.96$, GSA-TAP with $Q=2.5$, and LSA-TAP with $Q'=1.0$, respectively. From Fig. 6(a)–6(c) it is easy to see that the all the three distributions have the similar shape for the cases of TAP with $h=0.8$, GSA-TAP with $Q=2.5$, and LSA-TAP with $Q'=1.0$. However, the case of TAP with $h=0.96$ has significant difference from the other three cases, i.e., its variables n, t_w, and T have much larger ranges.

For understanding the difference between the case of TAP with $h=0.96$ and the other three cases, we show how the packets are distributed at the nodes in Fig. 7 where n_k denotes the average packets on those node with the same degree k. Obviously, there are much more packets accumulated at the hubs in the case of TAP with $h=0.96$ than that of other three cases. The reason is that $h=0.96$ is very close to the shortest path approach of $h=1$. As we know, in the case of $h=1$, packets tend to walk through the hubs and thus is easy to be accumulated there. Therefore, although the modified TAP with $h=0.96$ has smaller β_c than that of TAP with $h=0.8$, its statistical quantities such as queue lengths, waiting times, and travel times have much larger range, i.e., are not minimized, and thus cannot be considered as an effective routing approach. In the following, we will discard the case of TAP with $h=0.96$ and compare the efficiency among the other three cases.

An easy way to see their differences is to calculate the average travel time $\langle T\rangle$, which equals $\int_{T_{\min}}^{T_{\max}} TP(T)dT$. For comparison, we let β be the value of β_c for TAP with $h=0.8$ at each set of parameters. That is, β_c is not a constant but changes with the parameters, see Fig. 5 for details. Figure 8 shows how $\langle T\rangle$ changes with the parameters λ_0, A and ω where the "squares," "circles," and "triangles" represent the cases of TAP with $h=0.8$, GSA-TAP with $Q=2.5$, and LSA-TAP with $Q'=1.0$, respectively. From Figs. 8(a)–8(c) it is easy to see that the curve of GSA-TAP with $Q=2.5$ is the lowest, the curve of LSA-TAP with $Q'=1.0$ is in the middle, and the curve of TAP with $h=0.8$ is on the top, indicating that both the GSA-TAP with $Q=2.5$ and the LSA-TAP with $Q'=1.0$ are more effective than the TAP with $h=0.8$ and the

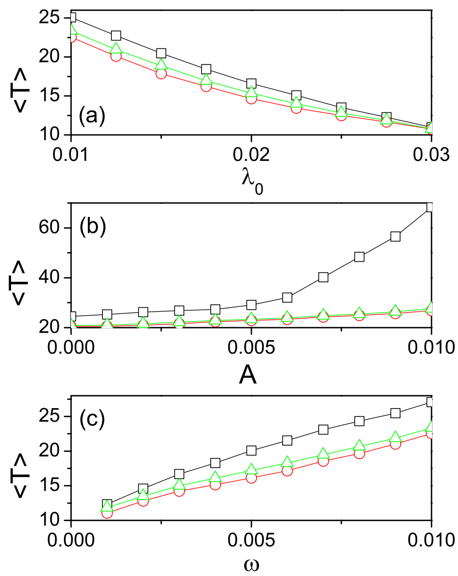

FIG. 8. (Color online) How the average travel time changes with different parameters, where β is set to be β_c for TAP with $h=0.8$ at the fixed parameters. (a) $\langle T\rangle$ versus λ_0 for $A=0.005$ and $\omega=0.01$, (b) $\langle T\rangle$ versus A for $\lambda_0=0.01$ and $\omega=0.01$, and (c) $\langle T\rangle$ versus ω for $\lambda_0=0.01$ and $A=0.005$. The "squares," "circles," and "triangles" represent the cases of TAP with $h=0.8$, GSA-TAP with $Q=2.5$, and LSA-TAP with $Q'=1.0$, respectively.

GSA-TAP with $Q=2.5$ is slightly better than the LSA-TAP with $Q'=1.0$. This point can be also confirmed by the average number of packets in network $\langle n\rangle$, which equals $\int_{n_{\min}}^{n_{\max}} nP(n)dn$, see Fig. 9 where the $\langle n\rangle$ for both the GSA-TAP and LSA-TAP are smaller than the corresponding value of $\langle n\rangle$ for the TAP.

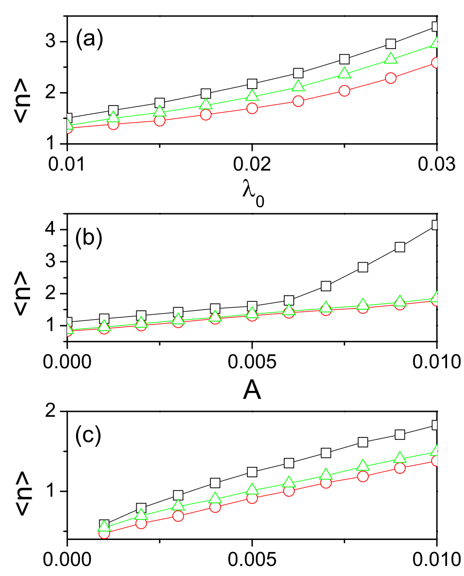

FIG. 9. (Color online) How the average number of packets in network changes with different parameters, where β is set to be β_c for TAP with $h=0.8$ at the fixed parameters. (a) $\langle n\rangle$ versus λ_0 for $A=0.005$ and $\omega=0.01$, (b) $\langle n\rangle$ versus A for $\lambda_0=0.01$ and $\omega=0.01$, and (c) $\langle n\rangle$ versus ω for $\lambda_0=0.01$ and $A=0.005$. The "squares," "circles," and "triangles" represent the cases of TAP with $h=0.8$, GSA-TAP with $Q=2.5$, and LSA-TAP with $Q'=1.0$, respectively.

V. DISCUSSION AND CONCLUSIONS

In this paper we focus on the performance of approaches through observing the delivering capacity parameter β_c and related statistical quantities. It should be noticed that these statistical quantities can be also used to probe a network's structure by the scaling features, see Refs. [3,29,34,35] for details. The fluctuations of traffic time series is another important quantity having statistical property [3,23,35]. Because of the stochastic feature of transport process, the fluctuations exist in both the case of constant generation rate in the previous studies and the case of varying generation rate Eq. (2). However, we must point out that Eq. (2) cannot be only considered as a fluctuation. More important is that it reflects the fact of periodic behaviors of human activities and it is allowable to have a fluctuation around the periodic behaviors.

In sum, we studied the effects of a time-varying packet generation rate on the efficiency of communication networks. The time-varying rate could be a result of patterns in human activities in a day or a season. In this case, enforcing a time-independent parameter h on the modified TAP [Eq. (1)] leads to an effective performance at $h=0.96$, but a better performing protocol based on the modified TAP would require a time-dependent parameter $h(t)$. However, for routing protocols, it would be advantageous to have a time-independent optimization parameter. Motivated by the modified TAP and noting that a quantity characterizing the instantaneous traffic flow is needed in the presence of a time-varying packet generation rates, we propose a class of protocols [Eq. (4)]. We studied two special cases in which the addition information are different: GSA-TAP that requires the global information of the instantaneous total number of packets in the system, and LSA-TAP that requires the local information of the queue lengths up to the next-nearest neighbors of a node ℓ to which a node intends to forward a packet. We found the optimized values of the time-independent parameters in GSA-TAP and LSA-TAP and compared performance of these self-adjusted TAPs with the modified TAP under identical packet generation conditions. Through both the β_c and the statistical quantities it is found that the GSA-TAP and LSA-TAP could find a less congested path for delivering packets and they perform better than the modified TAP. The trade off is that implementing GSA-TAP and LSA-TAP requires information more than the queue lengths at the next possible nodes in forwarding a message. The results at rapidly time-varying packet generation rates indicate that the GSA-TAP and LSA-TAP may also be an effective routing scheme for static packet generation rates.

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