2011 International Symposium on Nonlinear Theory and its Applications
NOLTA2011, Kobe, Japan, September 4-7, 2011

Dependence of Flow Stability on Synchronization of Path Switching in Autonomous Flow Networks

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Abstract– We consider the issue of the timing of control cycles for path switches by autonomous nodes in a communication network, and its effect on transport in the network. It is shown that when the network is close to saturation, traffic flow improves when the correlation between timing of path switches is reduced. The improvement is particularly apparent in the packet delay characteristics. The difference between synchronized and anti-synchronized cycles is only significant in a certain range of parameters at the onset of network saturation.

1. Introduction

More and more, electronic devices are being linked with network communications, from computers linked locally in local area networks and globally through the internet, to sensor networks, personal area networks, and body-area networks. The trend is expected to continue and even extend into new domains such as to cybernetic intra-body networks. A basic feature of these networks is that devices exchange packets of information using store and forward via one or more intermediate relay nodes. Mechanisms are needed to adapt the path of the data flow in.

Advanced computer networks use complex algorithms involving exchange of much information about the state of the network. In other cases, networked devices must make decisions on data paths independently with limited local information, based on recent monitoring of flow performance. Examples include sensor networks which cannot support complex control due to limited power and resources. Another example is overlay networks which have limited direct access to the state of the underlying network state. In such networks the path selection may involve random adaptive trial and error.

When adaptive mechanisms are used to switch paths according to the traffic flow, various forms of dynamical instability can arise [1-14]. In this paper we look at a common basic problem of path switching in networks of autonomous devices using random adaptive path switching. The problem concerns the timing of path switches. In particular, we consider a mechanism for path selection which involves periodic path switching cycles, with random choice of alternative relay path when the current path is not satisfactory.

When adaptive mechanisms are used to switch paths according to the traffic flow, various forms of dynamical instability can arise [1-14]. The problem of synchronization of switching in systems has been studied in various forms in many fields. In particular, the effects due to synchronization of path switching have been considered previously in various forms in telephone and computer networks. It is known that synchronization of path switching can cause oscillations and make paths unstable. However, the results of previous studies are not sufficient to understand our problem, because they make different assumptions about their network operation, or because the observations are anecdotal rather than analytical.

We aim to clarify the effects in a basic model which itself has practical significance, and moreover can provide a basis for studying more complex scenarios involving various other effects, where the effects of synchronization itself may be less obvious. In this paper, we consider the issue of the effect of synchronization on data flows in a model of two-hop multi-path networks. This model is the most fundamental model for analysis of the path synchronization dependence. This particular model is also directly relevant to certain classes of practical networks, including sensor networks and content distribution networks with two hop relay paths. We can also think of the relay nodes as corresponding to access points in a wireless sensor network, or routers in an overlay network.

The key aspect of this model is that control is autonomous in the sense that it does not directly know the state of other flows, or the interactions between flows in the network, and there is no explicit coordination between the multiple flows in the network, i.e., the flow controls do not communicate (regarding their decisions) with each other or with any central entity, and make their decisions independently. We clarify the effects of the synchronization of control cycles in such systems.

2. Model System

Specifically we consider the type of network topology, shown in Figure 1. A set of source nodes send flows to corresponding sink nodes, via a set of relay nodes. We assume that physical links exists between each pair of terminal and relay nodes, but there are no direct links between terminal nodes. The flow passes from the source node to a relay node and then to the receiver node. The relay nodes are fully connected with the source and receiver nodes, so that there is a path between every pair of sender and receiver via every relay node. Each node has an input buffer and an output buffer to store packets waiting to be processed or transmitted.

As for the autonomous control we consider the following control scenario. Each terminal node which is sending a stream of packets monitors its own flow, and if the flow is high, maintains the current path, and if the flow is low makes a switch to an alternative path. Monitoring and switching is executed in a periodic control cycle with period T_c, which includes a monitor period of length $T_m < T_c$. Fig. 2 shows a schematic of the control cycle. Switch of paths is executed at the end of the monitor period. Control cycles are said to be synchronous if the monitor intervals and switch instants coincide in time.

For simplicity, we assume the alternative path is chosen randomly from among the available paths, excluding the current path. This type of control has been used for example in Dynamic Adaptive Routing (DAR) [4].

The timing of path switches is defined as follows. In the in-phase case, the terminals all switch at the same time. In the anti-phase case, the sender terminals are each allocated a unique phase with equal separation (i.e. time-offset is $j \times T / N_f$, $j=1,2,\ldots,N_f$).

As for switch timing, we compare the following two models.

(1) In-phase: Switches are simultaneous.

(2) Anti-phase: Switches occur sequentially in some arbitrary order.

We assume that although the information and the decisions of the nodes is autonomous, the nodes are able to achieve either in-phase or anti-phase synchronization. In this paper, we do not consider the synchronization mechanism itself. We do note however, that for example it would be easily achieved in overlay networks in the internet where all nodes have a common network wide clock reference with jitter much less than the control cycle period, and each node has a unique identity which could be used to determine a unique phase.

For simplicity, we assume that traffic flows are between separate pairs of terminal nodes, with fixed and equal source traffic rate, and the channel link capacity C_l on each network link is fixed and equal. We also assume that nodes have input and output buffers with unlimited capacity. The relay nodes are assumed to have a limited relay capacity, C_r. This is a key parameter which determines the size of the "bottleneck" at a relay node.

Each relay node has N_f input and N_f output links. Hence, if there is no limit on relay capacity, any of the relay nodes could alone handle all N_f independent flows. On the other hand, for small relay capacity, then the number of flows, or the throughput, which can be handled by a single relay node will be limited.

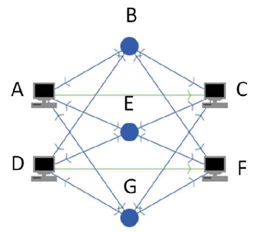


Fig. 1. Example of a 2-3-2 network. Two terminal nodes (A, D) each transmit a flow to corresponding peer nodes (C, F) via one of three intermediate nodes (B, E, G). Dark lines show network links between terminal nodes and relay nodes. Light lines show the end-to-end flows between the terminal nodes, A→C and D→F.

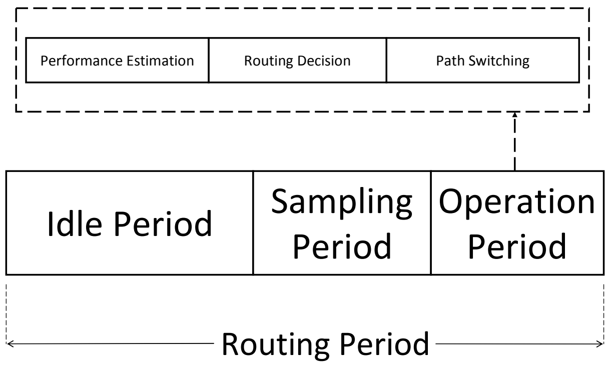


Fig. 2 Control cycle for path switch with period T_c and monitor period of length $T_m < T_c$.

A critical value of relay capacity C_r can be estimated as

$$C_r = \frac{N_f R_s}{N_r} \quad (1)$$

where N_f is the number of flows, R_s is the source flow rate, and N_r is the number of relay nodes. In this example, the $N_r = N_f/2$, so the critical value of C_r is $2 \times R_s$. As the relay capacity is reduced toward this value, we can expect it to become more difficult for the system to reach a state which can transport all the flows.

3. Simulation Analysis

As a specific numerical example, we consider the case of a 10-5-10 network, consisting of $N_f=10$ terminal node pairs and $N_r=5$ relay nodes. Parameter values are shown below in Table 1. We use general units defined with respect to unit time step. In this example, the critical value of C_r is $2 \times R_s = 16$.

We examine the delay behavior. This is obtained by comparing the sequence number of a received packet with the sequence number of the packet sent from the corresponding sender terminal in the same time instance. This shows by how many packets the receiver flow is delayed compared to the sender flow.

TABLE I. SIMULATION PARAMETERS

Parameter	Value
Number of Flows (N_f)	10
Number of Relay nodes (N_r)	5
Source rate (Rs)	8
Link capacity (C_l)	8
Relay capacity (C_r)	16, 20,40
Buffer capacity	Unlimited
Path switch period (T_c)	40
Switch-synchronization type	In-phase, Anti-phase

We show the systematic dependence of delay on relay capacity in Fig. 3. We plot the maximum (D_{max}) and minimum (D_{min}) values of delay at receiver terminals as a function of the relay capacity C_r. We first note that the results here for D_{min} are the same for In-phase (D_{min}-*In*) and Anti-phase (D_{min}-*Anti*). For large capacity, there is no variation of delay. For small capacity, the switch timing does not seem to have any effect on the delay. For intermediate values of relay capacity, the anti-phase timing exhibits less delay variation and more stable behavior overall.

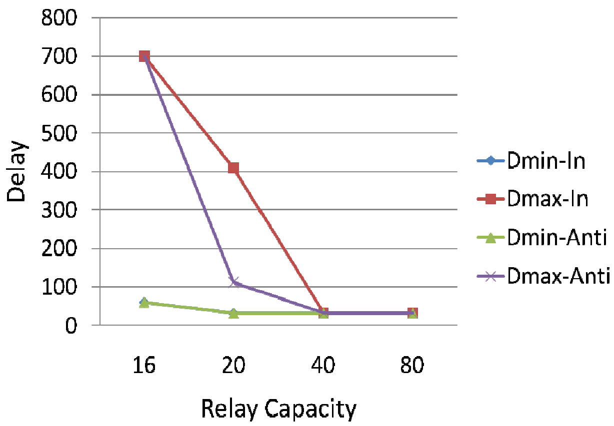
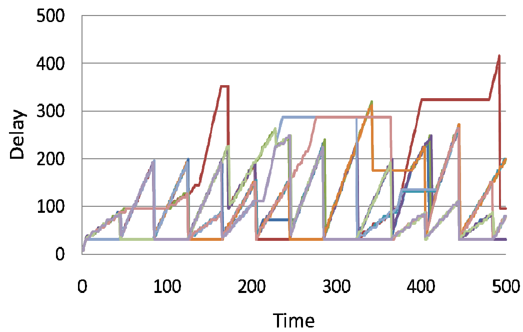
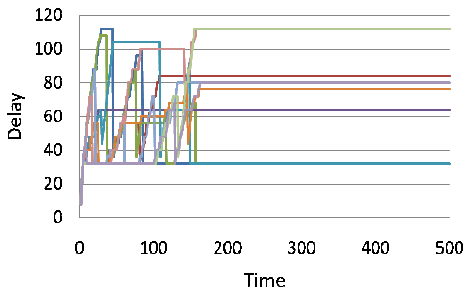


Fig. 3. End-to-end Delay *(D_{min}, D_{max})* versus Relay Capacity (C_r). (Dmin-In: Minimum value of delay in the case of in-phase switch. Dmax-In: Maximum value of delay in the case of in-phase switch. Dmin-Anti: Minimum value of delay in the case of anti-phase switch. Dmax-Anti: Maximum value of delay in the case of anti-phase switch. Note that the Dmin-In and Dmin-anti lines are identical and so only one line is visible.)

Figure 4 shows examples of the variation of the delay for each flow in the case of relay capacity C_r = 20, approaching the critical value of C_r =16. It can be seen that the in-phase case has not reached a steady state after 500 time steps (500/40 ~ 12 control cycles). On the other hand, the anti-phase mode converges faster to a steady state. Moreover, during the transient stage, the variation of delay is smaller for the anti-phase case compared to the in-phase case.



(a) Example of In-phase switching



(b) Example of Anti-phase switching

Fig. 4. Delay (D) versus time, for all flows (Number of flows $N_f = 10$, Relay node capacity $C_r = 20$. The line for each flow is shown with a different color to make it easier to visually identify the lines. Time is in units of path switch cycle period.)

4. Discussion

Based on the above observations, we distinguish three characteristic regimes of different behavior

- Low-load: The performance is similarly good for both types of synchronization, in-phase (synchronous) or anti-phase (asynchronous).
- Full-load: Anti-phase switching performs better than in-phase switching.
- Over-load: The performance is similarly bad for

both types of synchronization.

In our example, with all links having equal bandwidth, $C_l=8$, relay capacities $C_r \sim 16, 20, 40$ correspond to the three different regimes. Numerical results confirm that if the capacity of some links are reduced, then the onset of full-load and over-load regimes correspond to lower values of relay capacity.

When the system approaches the critical value, it becomes more difficult for the system to reach a solution, and the effect of switching timing becomes more significant. This effect is large on the fluctuation of packet delay observed at the receiver nodes. The anti-phase control converges to a steady solution, but the in-phase control does not.

The differences due to timing control are more manifest in the delay values, than in the throughput values. This is because the throughput is an aggregate of flow spread over multiple relay paths. On the other hand the delay values manifest propagation delays due to congestion at individual relay nodes.

It is easy to see from the symmetry of the problem that there could be many such solutions. Which particular solution (i.e., which particular set of delays) the system converges to depends on the particular combination of random choices made by the terminal nodes.

Although the in-phase control does not converge, if we look at a particular receiver terminal we see that the delay intermittently decreases. This maybe still be satisfactory behavior depending on the application. It would be a problem for jitter sensitive real time applications such as voice, but the effect of the fluctuations could be largely overcome by buffering at the receiver terminal.

5. Conclusions

We examined a basic model of periodic path switching by autonomous nodes in a network, and showed the effects of synchronization of path switching.

When the effect of each flow on other nodes sharing its path is not sufficiently small or slow, then the switching of paths affects the behavior of other flows and the stability of the network. Our model clearly shows that when the load on the network is large, the temporal correlation of control cycles can affect the size of the change in flow distribution in each control cycle, and so affect the convergence to a satisfactory balance of flows. In particular, we showed that traffic flow can be improved when the timing of path switches are synchronized out of phase, that is, they are anti-correlated.

More specifically, we showed how the manifestation of synchronization effect depends on key parameters relating the number of flows in the network, the number of paths, and the capacity of the paths. We also showed that for this model which has no packet loss or re-send mechanism, the effect of synchronization on the end-to-end throughput is always small. On the other hand, there can be large differences in the distribution of packet delays. The change in the relative phase of synchronization can cause a shift in the critical load condition corresponding to the abrupt onset of large delays in the network. Further, we make the important observation that in regimes where the system is over-loaded, the effect of switch timing is less significant. This result for over-loaded networks seems analogous to the reported phenomenon in road networks that the correlation between traffic signals has little effect on the throughput when the roads are saturated [13,14]. Such similarities are an interesting area for future consideration in the context of universal behavior of flows in networks with synchronized path switching.

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