

A Simple Time Synchronization Scheme for Satellite Clusters in Formation Flying

N. Nagarajan
Nanyang Technological University
Singapore; +65 67906860
enara@ntu.edu.sg

Dao Thi Hong Diep
Nanyang Technological University
Singapore; +65 67906585
daot0003@ntu.edu.sg

ABSTRACT

Future communications may use many small satellites flying as a cluster. Such a cluster helps to synthesize very large antennae in space, wherein each satellite becomes the node or element of the antenna structure. A key factor in such a cluster, is the positioning of satellites in absolute as well as relative terms and the time synchronization between them. Ultra Wide Band (UWB) techniques have promising applications for small satellites, because they require only a very small power and support both navigation and communication. In this paper a simple technique i.e ‘transmit and listen’ method is used to demonstrate the time synchronization between the members of the cluster. One member satellite, ‘mother’, is assumed to have the capability to retransmit or reflect back the signals from the ‘child’ satellites. To begin the process of synchronization, a child satellite transmits a pulse and starts a counter. The pulse reaches the mother and gets reflected back and received by the same child after a time equal to the round-trip delay. Using the time instants of the transmitted and received signals the clock offset is calculated. The offset is partially or fully corrected in the next transmission of the signals. By this process, the clock of child slowly gets synchronized with the mother. Matlab simulations show that synchronization is achieved within about 50 cycles. Once synchronized, subsequent pulses can be used to calculate the distance and thus maintain the formation using an appropriate relative navigation algorithm.

INTRODUCTION

In a network or a cluster, be it for terrestrial or satellite communications, there is a need for ‘self-organization’. The ‘self-organization’ refers to the process of adjusting and re-adjusting certain features of each member so that finally there is a harmony in the functioning of the members. A prominent feature in communication and navigation is the ‘time synchronization’ which refers to how accurately the time stamps from each member are matched to those from others and finally with reference to the absolute time. Once an accurate time synchronization is achieved, a timing pulse locally generated can be easily compared with the one received from another member and this leads an accurate estimation of the distance.

Over the decades, many researchers have studied the problem of time synchronization in biological systems. One of the most interesting paper in on the time synchronization between fireflies [1]. The synchronization among fireflies is explained using the concept of “Pulse Coupled Oscillators”. In a pulse-

coupled oscillator, the phase function $\phi(t)$ evolves linearly with time. When it reaches a threshold ϕ_{th} the oscillator is said to ‘fire’ meaning that it transmits a pulse and resets its phase. Without going into the further details, it will suffice to say that the paper establishes a stability criteria linking the propagation delay to a preset ‘refractory period’. The accuracy in this approach is only limited by the propagation delay. In case of a cluster with members separated by a distance of about 50m the propagation delay is about 0.17 μ sec. The motivation for the work reported here is the interesting manner in which the time synchronization is explained to occur in fireflies and also the growing prospects for satellite based communication using clusters or even ‘swarms’ of satellite. In such clusters or swarms used to synthesize a large antenna structure, each satellite forms the node and its distance need to be known accurately to compensate for the time delay to ensure accurate electronic steering of the beams [2].

The Ultra Wide band (UWB) techniques are capable of providing promising applications for formation flying using cluster of satellites. The main advantage of UWB techniques is that they can be used both for navigation as well as communications at a speed of a few megabits per second. Further, since the UWB pulse is a very small pulse, with a very small average power consumption the transceivers can work over a distance of few hundred meters [3].

This paper is organized as follows. Following the introduction, the next section addresses the basics of ‘Transmit and Listen’ method. The basic equations to compute the one way and round-trip delay are derived and the clock offset equations are formulated. One-step and Multi-step offset correction strategies and their limitations are addressed. A simple error analysis is performed to assess the accuracy of synchronization as a function of the clock frequency and correction factor. All the formulations in the second section assume that there is only an offset in the occurrence of the timing pulses, but the clock frequency is same on all the member satellites. In reality the clock frequencies may be slightly different on different satellites due to the crystal stability. The third segment of the paper addresses the effect of clock frequency drift and suggests a scheme to correct for that effect. Then follows the Matlab simulation results for a network of 5 members. Based on the simulations, a strategy is suggested to periodically compute the clock offset and drift. The first phase is termed as ‘correction phase’ during which the clock offset and drift are computed. The second phase is termed as ‘normal phase’ during which the UWB pulses are used for navigation and communication assuming that synchronization is achieved. The paper concludes with the summary of simulation results.

FORMULATION

Transmit and Listen method

As in Figure 1, let us start with just two members (A and B) and establish the method to achieve time synchronization. In the two-member network shown below, B is the mother and A is the child. Whenever A wants to synchronize with respect to B, it transmits a pulse which is reflected back by mother. Mother satellite also periodically transmits pulses towards the child and this is shown by the dotted lines. It is assumed, for the time being, that the clocks on both the satellites are stable and have the same frequency, but the pulses are not synchronized. Hence the first task for A is to calculate its own clock offset based on the pulses transmitted and received by itself, and the pulse transmitted by B and received by A. Once the clock offset is calculated, this will be used in timing the

transmission of the subsequent pulses to be transmitted from A.

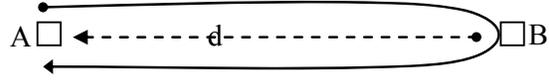


Figure 1: Basic two-member network

Clock Offset Calculations

Figure 2 shows the typical timing of the transmitted and received pulses for the scenario depicted in Figure 1. It is assumed that A and B have internal clocks working at a frequency of f_c . The clock period is then $T=1/f_c$. Let t_A be the instant of a pulse transmission from A. Once a pulse is transmitted from A the next pulse will be transmitted after NT where N is sufficiently longer the round-trip time required between A and B. Similarly B transmits pulses at regular interval of NT . In a perfectly synchronized system, t_A and t_B should ideally be at the same instant. Due to an unknown offset τ , let us assume that B transmits at t_B . As soon as the pulse is transmitted from A, it initiates a local counter using its own clock. Now the signal transmitted from A reaches B, gets reflected back and reaches A at t_{AA} . Similarly the pulse transmitted from B reaches A at t_{BA} .

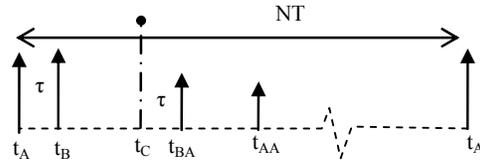


Figure 2: Pulse Timings

If n_{AA} and n_{BA} are the contents of the counter read at t_{AA} and t_{BA} , we have

$$\begin{aligned} t_{AA} &= n_{AA}T = \frac{2d}{c} \\ t_{BA} &= n_{BA}T = \tau + \frac{d}{c} \\ t_c &= t_{AA}/2 = \frac{d}{c} \end{aligned} \quad (1)$$

The clock offset τ is then obtained as,

$$\tau = \left(n_{BA} - \frac{n_{AA}}{2} \right) T \quad (2)$$

The clock offset in terms of counts is given by,

$$n_{offset} = \left(n_{BA} - \frac{n_{AA}}{2} \right) \quad (3)$$

Single Step Offset Correction

Having calculated the offset, A can delay or advance the subsequent transmission of the pulses. For the situation shown in Figure 2, A will have to delay the next pulse to achieve synchronization. The synchronization is verified by calculating the offset once again in the subsequent cycle and establishing that the offset is within acceptable limits.

Thus, the time of transmission of the second pulse from A, will be $t_{A,2}$,

$$\begin{aligned} t_{A,2} &= t_A + NT + \tau \\ &= t_A + NT + \left(n_{BA} - \frac{n_{AA}}{2} \right) T \end{aligned} \quad (4)$$

The time $t_{B,2}$ for the second pulse from B is,

$$\begin{aligned} t_{B,2} &= t_B + NT \\ &= t_A + NT + \tau \\ &= t_A + NT + \left(n_{BA} - \frac{n_{AA}}{2} \right) T \end{aligned} \quad (5)$$

From the equations (4) and (5) it is observed that the pulse emissions from A and B, after ‘offset-correction’, occur at the same instant confirming synchronization. Therefore the offset computed in the second cycle will be zero. Assuming that the clocks of A and B do not drift, ‘synchronization’ is said to have been achieved.

Progressive Offset Correction

In a network or a cluster where the number of satellites are small and hence the formation is not congested, a single step correction would be efficient as there may not be interferences due to factors like multi-path (this is part of the future investigations). Anticipating such errors, another strategy, i.e. ‘progressive offset correction’ is also analyzed. In stead of applying the full offset calculated in equation (2) only a fraction of the offset is corrected (say $k\tau$) where $0 < k < 1$. Under this strategy, the offset remaining at the end of the cycle is $(1-k)\tau$. Therefore $t_{A,2}$, $t_{B,2}$ are given by,

$$t_{A,2} = t_A + NT + k\tau \quad (6)$$

$$\begin{aligned} t_{B,2} &= t_B + NT \\ &= t_A + NT + \tau \end{aligned} \quad (7)$$

Therefore the offset which was τ in the first cycle, becomes $(1-k)\tau$ in the second cycle. After partially correcting this, the offset in the third cycle becomes $(1-k)^2\tau$. The partial offset strategy thus leads to a situation wherein the offset (τ_p) in cycle p will be,

$$\tau_p = (1-k)^{p-1} \tau \quad (8)$$

Multi-member Network

Formation flying involves maintaining the relative position of a number of satellites. The number may range from a few satellites to a few tens or hundreds of satellites [3]. In all such formations, shown in Figure 3, it is assumed that the central satellite takes the role of ‘mother’ and its clock frequency is assumed to be very stable. The offset of each child satellite is thus referenced to ‘mother’. After a few cycles the transmissions from each child gets synchronized to mother. This situation is very similar to ‘fireflies’.

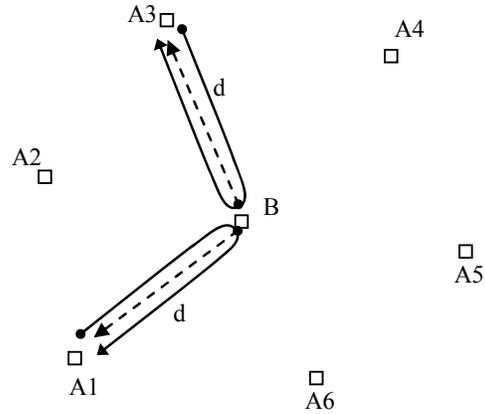


Figure 3: Multi-member Network (Formation Flying)

Synchronization with Unequal Frequencies

So far in the formulation it has been assumed that the clock frequencies of the members of the network are identical which is an ideal case. In reality there will definitely be some small differences due to factors like crystal quality, age, operating temperature etc. This section analyses the effect of frequency differences on the synchronization and formulates the equations to compensate that. Let the frequency of A be different from f_c (of mother) resulting in a period $T+\delta$. Because of this, pulses of A will be emitted at an interval of $N(T+\delta)$ while those from B will be at an interval of NT .

Table 1: Simulation Parameters

Parameter	Nodes				
	1	2	3	4	5
Clock Period (nSec)	0.1	0.1-- 0.75e-4	0.1+ 1.1e-4	0.1-- 0.85e-4	0.1-- 0.65e-4
Clock freq (GHz)	10	10.0075	9.989	10.0085	10.0065
Initial Offset (Counts)	0	5504	3496	5504	7004
Node Status	M	C	C	C	C

Legend: M – Mother, C - Child

The pulses are transmitted at an interval of 10^6 clock counts (100 μ sec based on the frequency of the mother node) which is sufficiently larger than the round-trip time. Table 1 shows the simulation parameters.

Case Study – Identical Clock Frequencies

The first study is to evaluate the synchronization under ideal conditions, i.e all the node have the same clock frequency of 10 GHz. In this case the synchronization effort is only to correct the initial offsets shown in Table 1. Figure 4 shows the progress of synchronization with progressive correction ($k=0.1$) for two nodes 3 and 5. Even with a low correction factor, synchronization is achieved within about 50 cycles (5 msec). The steady state offset is depicted in Figure 5.

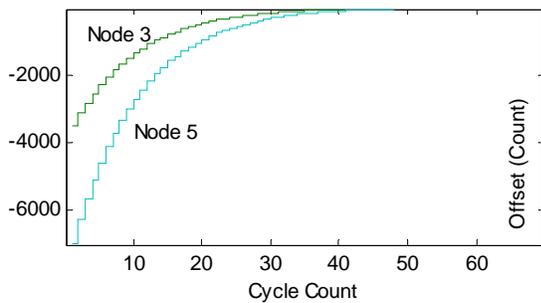


Figure 4: Synchronization with identical clock frequencies

Figure 5 shows that the offset values do not reach zero as given by (8), but the values stabilize at a count of 9. This corresponds to a time offset of 0.9 nsec. This is due to the discrete implementation of the offset calculation.

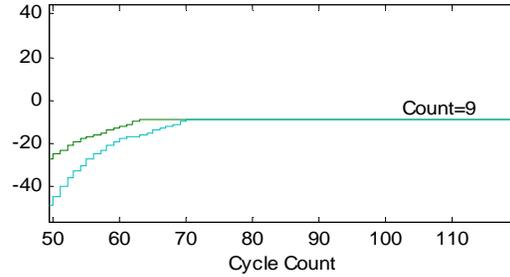


Figure 5: Steady State offset for Synchronization with identical clock frequencies (k=0.1)

In the present work the offset is calculated in terms of ‘counts’ of clock and corrected by factor k. In this case a counter value of 9 with $k = 0.1$ leads to a correction of 0.9 which becomes zero when changed to integer count. Thus for any offset less than 10, the correction becomes zero.

Table 2 shows the final offset count for different k values. It is seen that for the range $1 > k > 0.4$, the steady state offset is 1 count (0.1 nsec). Therefore when progressive correction is required k could be kept at 0.7 or 0.8.

Table 2: Steady State Offset Counts

k	1	0.9	0.8	0.7	0.6	0.5	0.4	0.3	0.2	0.1
Offset	0	1	1	1	1	1	2	3	4	9

Case Study – Different Clock Frequencies

After establishing the basic synchronization strategy under ideal conditions, the next study is to consider a more realistic situation in which the clock frequencies of the nodes could be slight different due to factors like crystal quality, age, temperature etc. Since the children nodes are expected to synchronize with reference to mother node, the frequency of the mother node is set to 10GHz. The frequency of child node is relatively disturbed as shown in Table 1. Figure 6 shows the offset for single-step offset correction. Even after correction, the offset of node 3 for instance, is stabilized at a count 1100 (110 nsec). This is due to the term ‘N δ ’ of equation (10). For the simulation, $N = 10^6$ and $\delta=1.1e-4$ for node 3. For the same situation, Figure 7 shows the offset (in counts) when $k = 0.7$. Applying

equation (12) the steady state offset is equal to $N\delta/k$ and take a value of (157.1 nsec).

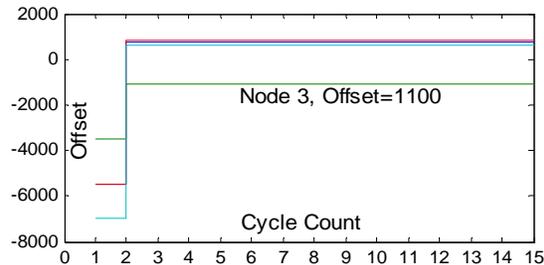


Figure 6: Steady State offset for Synchronization with different clock frequencies ($k=1.0$)

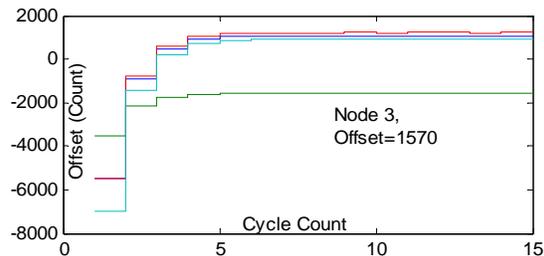


Figure 7: Steady State offset for Synchronization with different clock frequencies ($k=0.7$)

The final simulation study is to assess the correction strategy proposed to compensate the effect of clock frequency differences. From the earlier simulations it seen that for $k = 0.7$ it takes about 10 cycles to stabilize. Hence cycles between 10 to 50 are used to confirm that the offset is stabilized and at the end of 50th cycle, the additional correction (or ‘look-ahead’ correction) as suggested by equation (12) is applied. Figure 8 shows the excellent performance of this strategy.

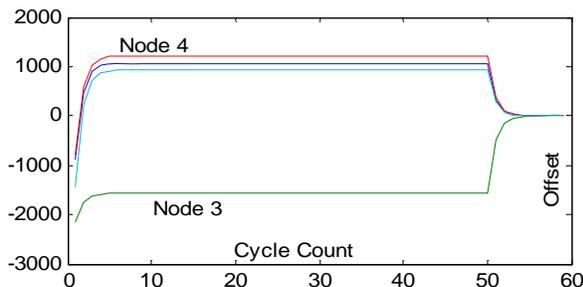


Figure 8: Synchronization with Look-ahead corrections

CONCLUSION

Motivated by the interesting fireflies’ synchronization as reported in the literature, basic equations to derive the clock offset using ‘transmit and listen’ method have been formulated. The formulation establishes the effect of partial or progressive corrections assuming ideal environment. As a more practical case, the offsets arising from different clock frequencies have been formulated and analyzed. This leads to a simple ‘look-ahead correction’ strategy to fully compensate for the effect of frequency offsets. Simulations, used to verify the derivations, show that synchronization accurate to a few clock periods can be realized. As the performance is dependent on the ability to ‘transmit and listen’, an experimental set-up is being planned with UWB antenna, transceivers and high frequency counters, with short node separation (a few meters).

References

1. Tyrrell, A., Auer, G. and Bettstetter, C., “Fireflies as Role Models for Synchronization in Ad Hoc Networks”, 1st Bio-Inspired Models of Network, Information and Computing Systems, Dec 2006., Pages 1-7.
2. Bekey, Ivan., Advanced space system concepts and technologies : 2010-2030+, Aerospace Press, 2003
3. John Carl Adams, Walt Gregokch, Larry Capots, Darren Liccard, “Ultra-Wideband for Navigation and Communications”, Proceedings of IEEE Aerospace Conference, 10-17 March 2001, Volume 2, Page(s):2/785 - 2/792.