Quadrotors Formation Control A Wireless Medium Access Aware Approach

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A Wireless Medium Access Aware Approach

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Abstract In this paper, the impact of the medium access protocols on the average consensus problem over wireless networks for a group of quadrotors is established. The stabilization of each helicopter is guaranteed using a simple and bounded nonlinear control strategy. We study the case of a group of quadrotors communicating over a wireless network considering both directed and undirected graphs of information flow. It turns out that the media access control (MAC) protocols have a direct impact in both convergence time and average consensus solution, *i.e.* the solution of the average consensus is no longer the average of the initial conditions. It will be shown that the solution for the average consensus problem over a wireless network depends directly on the MAC algorithm. Simulations are provided to demonstrate the theoretical results. In addition, to validate the control strategy some experimental tests have been carried out to control the yaw angle of two quadrotors.

Keywords Formation control · medium access protocols · wireless network

1 Introduction

Small Unmanned Aerial Vehicle (UAV) teams are excellent candidates for improving efficiency and reducing risk in search and rescue missions in unknown or dangerous environments. The deployment of small UAV teams offers certain advantages over both individual vehicles and vehicles of larger size. Small vehicles can be more easily and cheaply deployed than larger ones, and can maneuver effectively in confined spaces. Size restrictions necessarily affect payload and range capabilities, but for applications in a finite domain that is not easily accessible, the small multi-vehicle platform can be quite advantageous for rescuers. In particular, the maneuverability and speed of small rotorcraft enable their use in wilderness

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areas over uneven and forested areas, as well as in and around buildings for fire or natural disaster rescue in urban environments.

In the particular case of multi-agent (multiple aerial vehicle) consensus problem, most of the literature is focused on modeling the information flow network using either fixed or switching topologies [1], [2], [3], [4], [5], among others. This means that the communication network does not suffer of time delay and packet drop problems. The main difference between fixed and switching topologies is that the switching topology case takes into account that every aerial vehicle has a limited range of interaction with its neighbors, *i.e.*, the mobility of the aerial vehicles affects the information exchange topology.

The distributed nature of multiple robot control system over wireless networks represent an interesting research problem. Data loss, data corruption and time delay over lossy network are key factors that may lead to performance degradation and even cause instability. Recent work on networked control over noisy communication channels includes [6], [7]. In most of the cases the packet drop phenomena is modeled as a random process without any specification of its probabilistic distribution [8], [9]. In [10], the authors consider the packet drop process as a Bernoulli process and develop stability conditions under these conditions. Another way to model the packet loss phenomena has been described in [11], where a Markov chain has been used to model the packet dropout process.

This paper addresses the issue of packet loss as well as packet delay in a multi-agent aerial system considering a wireless network. For this end, we use the widely adopted network simulator (NS2) which provides a rich simulation environment modeling the different network communication layers: the physical layer (modulation, frequencies, signal and radio propagation models, wired and wireless channels, ...), link layer (different medium access control algorithms: TDMA, CSMA/CD, CSMA/CA, ALOHA, ...), routing layer (routing protocols over wired and wireless networks as well as mobile ad hoc networks), transport layer (TCP, UDP, RTP, etc.), and the application layer with a rich sample of applications for typical traffic generation scenarios. It will be assumed, for simplicity, that every agent in the multi-vehicle system broadcasts its information to its neighbors considering a fixed topology of information exchange, *i.e.* the mobility of the vehicles does not affect the information flow network. It is assumed that the neighbors of the i^{th}-quadrotor are always in broadcasting range. Different network media access control protocols have been designed for wireless networks. Likewise, in this paper, we analyze the impact of the following algorithms on the multiple quadrotor average consensus problem: Carrier sense multiple access with collision avoidance (CSMA/CA) and time division multiple access (TDMA).

The outline of the paper is as follows: A brief description of the multi-quadrotor dynamics and control over perfect communication links is introduced in section 2. In Section 3, the multi-quadrotor average consensus over wireless network analysis is presented. A stability analysis to improve the convergence of the consensus is proposed in section 4. Simulation results are illustrated in section 5. And finally, conclusion and future work are discussed in section 6.

2 Multi-quadrotor consensus

2.1 Quadrotor dynamic model and control scheme

Let us consider a group of $N-$quadrotor helicopters with the following dynamical model [12], [13]:

$$\ddot{z}_i = \mathbf{F}_i \cos(\theta_i)\cos(\phi_i) - 1; \qquad \ddot{\psi}_i = u_{\psi_i} \tag{1a}$$
$$\ddot{y}_i = \mathbf{F}_i \cos(\theta_i)\sin(\phi_i); \qquad \ddot{\phi}_i = u_{\phi_i} \tag{1b}$$
$$\ddot{x}_i = -\mathbf{F}_i \sin(\theta_i); \qquad \ddot{\theta}_i = u_{\theta_i} \tag{1c}$$

where (x_i, y_i, z_i) and $(\phi_i, \theta_i, \psi_i)$ represent the position and orientation of the $i^{th}-$quadrotor, respectively. $\mathbf{F}_i$ denotes the thrust force vector and $u_{\psi_i}, u_{\phi_i}, u_{\theta_i}$ the generalized torques.

To stabilize the previous system, we use the following control laws,

$$\mathbf{F}_i = \frac{-\sigma_{b_{1_i}}(k_{1_i}\dot{z}) - \sigma_{b_{2_i}}(k_{2_i}(z_i - z_i^d)) + 1}{\cos(\phi_i)\cos(\theta_i)} \tag{2a}$$
$$u_{\psi_i} = -\sigma_{b_{3_i}}(k_{3_i}\dot{\psi}_i) - \sigma_{b_{4_i}}(k_{4_i}(\psi_i - \psi_i^d)) \tag{2b}$$
$$u_{\theta_i} = -\sigma_{b_{5_i}}(k_{5_i}\dot{\theta}_i) - \sigma_{b_{6_i}}(k_{6_i}\theta_i) + \sigma_{b_{7_i}}(k_{7_i}\dot{x}_i) + \sigma_{b_{8_i}}(k_{8_i}x_i) \tag{2c}$$
$$u_{\phi_i} = -\sigma_{b_{9_i}}(k_{9_i}\dot{\phi}_i) - \sigma_{b_{10_i}}(k_{10_i}\phi_i) - \sigma_{b_{11_i}}(k_{11_i}\dot{y}_i) - \sigma_{b_{12_i}}(k_{12_i}y_i) \tag{2d}$$

where $|\sigma_{b_{m_i}}(s)| < b_{m_i}$ is a saturation function $k_{m_i}, b_{m_i} > 0$; $m = 1, \ldots, 12$; are constant, z_i^d and ψ_i^d are the desired altitude and heading for the $i^{th}-$quadrotor, respectively. It was proved in [14] that the nonlinear control laws in (2) guarantee the stabilization of the $i^{th}-$quadrotor in closed loop system such that

$$\lim_{t\to\infty} z_i = z_i^d; \qquad \lim_{t\to\infty} x_i = 0$$
$$\lim_{t\to\infty} \psi_i = \psi_i^d; \qquad \lim_{t\to\infty} y_i = 0$$

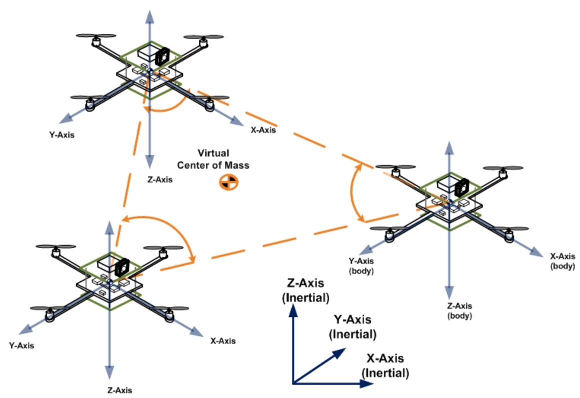

Fig. 1: Quadrotor platoon

2.2 From individual to collective behavior

In order to model the interactions among helicopters, a graph-based theoretical approach has been considered. Notice that the closed-loop system, (1)-(2), for the i^{th}-quadrotor can be expressed with the following kinematic model

$$\dot{\mathbf{x}}_i = \mathbf{u}_i \qquad \forall i = 1,..,N;$$

where $\mathbf{x}_i$ is the state vector and $\mathbf{u}_i$ represents the control input vector.

Multi-quadrotor consensus is achieved using the following algorithm

$$\mathbf{u}_i = -\sum_{j\in\mathcal{N}_i} (\mathbf{x}_i - \mathbf{x}_j) \tag{3}$$

where $\mathcal{N}_i$ is the set of vehicles transmitting their information to the i^{th}-quadrotor. Noticed that (3) ensures the consensus agreement in the sense of $\lim_{t\to\infty} |\mathbf{x}_i - \mathbf{x}_j| = 0$. Hence, the position consensus among quadrotors yields

$$\dot{\bar{\mathbf{x}}} = -\mathcal{L}\bar{\mathbf{x}} \tag{4}$$

where $\mathcal{L}$ is the Laplacian matrix of the information exchange graph, more details see [13,15].

Therefore, the controllers in (2) can be improved to the case of multi-quadrotor consensus with the form

$$\mathbf{F}_i = \frac{-\sigma_{b_{1_i}}(k_{1_i}\dot{z}) - \sigma_{b_{2_i}}\left(k_{2_i}\left(\sum_{j\in\mathcal{N}_i}(z_i - z_j) - z_i^d\right)\right) + 1}{\cos(\phi_i)\cos(\theta_i)} \tag{5a}$$

$$u_{\psi_i} = -\sigma_{b_{3_i}}(k_{3_i}\dot{\psi}_i) - \sigma_{b_{4_i}}\left(k_{4_i}\left(\sum_{j\in\mathcal{N}_i}(\psi_i - \psi_j) - \psi_i^d\right)\right) \tag{5b}$$

$$u_{\theta_i} = -\sigma_{b_{5_i}}(k_{5_i}\dot{\theta}_i) - \sigma_{b_{6_i}}(k_{6_i}\theta_i) + \sigma_{b_{7_i}}(k_{7_i}\dot{x}_i) + \sigma_{b_{8_i}}\left(k_{8_i}\sum_{j\in\mathcal{N}_i}(x_i - x_j)\right) \tag{5c}$$

$$u_{\phi_i} = -\sigma_{b_{9_i}}(k_{9_i}\dot{\phi}_i) - \sigma_{b_{10_i}}(k_{10_i}\phi_i) - \sigma_{b_{11_i}}(k_{11_i}\dot{y}_i) - \sigma_{b_{12_i}}\left(k_{12_i}\dot{\sum}_{j\in\mathcal{N}_i}(y_i - y_j)\right) \tag{5d}$$

which implies that

$$\lim_{t\to\infty} |(z_j - z_i)| = z_i^d; \qquad \lim_{t\to\infty} |(x_j - x_i)| = 0$$
$$\lim_{t\to\infty} |(\psi_j - \psi_i)| = \psi_i^d \qquad \lim_{t\to\infty} |(y_j - y_i)| = 0$$

In order to illustrate the performance of the previous control strategy, simulations were carried, over the $x-$axis, out considering a 10-quadrotor platoon over a perfect communication network (no delay, no packet loss) with cyclic topology. The initial conditions are $x_i(0) = i$, $\forall i = 0, 1, ..., 9$. Since the $x-$ and $y-$ axis have a similar behavior, only the $x-$axis consensus performance graphs will be presented.

Figure 2 shows the consensus response. Observe in this figure that the convergence time is small and the solution of the average consensus over the $x-$axis is the average of the initial conditions, *i.e.*, the platoon achieves consensus to 4.5m. Thus, the previous nonlinear control laws guarantees the position synchronization of the quadrotor platoon.

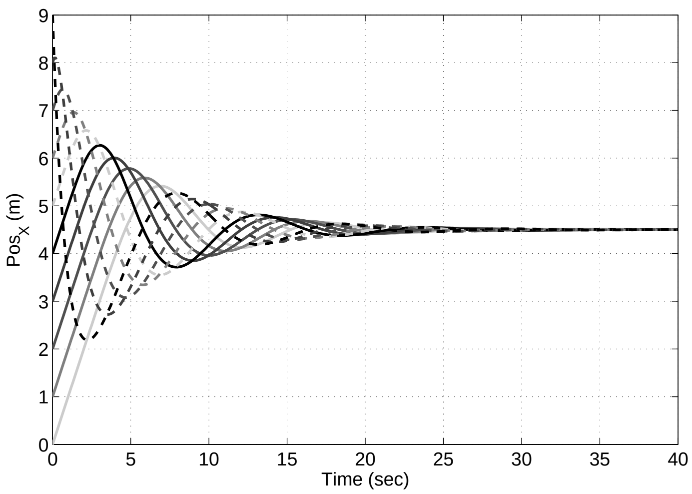

Fig. 2: Multiple quadrotor consensus using perfect communication

In literature, several simulations using the previous (similar or different) controllers have been carried out in order to prove the stability of the consensus or of the flight formation trajectory, see [16], [17], [18], [19]. Most of the assumptions in these works are considering wireless and perfect communication between the vehicles. In addition, the main results in flight formation are in general illustrated only in simulations.

As it is known, in a real multi-vehicle flight formation system, each aircraft collects information from its sensors and then exchange its information, employing wireless communication, with other autonomous vehicles in the network. Packet delay and packet loss in wireless becomes a major issue of study that must be taken into account when stabilizing multi-aerial vehicles. The goal of this work is to analyze, the impact of the wireless network communication in the real-time multi-vehicle consensus problem.

3 Analysis of wireless communication impact on flight formation

Let us consider the case of a N-quadrotor formation flying over a wireless communication channel. From the automatic control point of view, the key factors when using wireless channels are: end-2-end time delay, packet dropout rate, network connectivity and noise. Let us assume that the mobility of the agents does not affect the network connectivity and neglect the noise from sensors. Then, we focus our attention on the packet dropout rate and the end-2-end time delay problems. It has been shown in the communications literature [20], [21] that both packet dropout rate and the end-2-end time delay are determined by the Medium Access Control protocols. Our study considers two common technologies for wireless communications: CSMA/CA used in IEEE802.11 and TDMA used in GSM.

3.1 CSMA/CA

This is a distributed random access algorithm used in many standards such as Wifi IEEE802.11. This scheme uses a carrier sense multiple access with collision avoidance (CSMA/CA) mechanism for resolving the problem of access to the communication medium. This implies that when a node detects a collision, it stops transmitting and waits for a random time before retransmitting. More precisely, the protocol CSMA/CA works as follows [22]:

1. a carrier sensing scheme is used
2. a data station that intends to transmit, sends a jam signal,
3. after waiting a sufficient time for all stations to receive the jam signal, the data station transmits a frame
4. while transmitting, if the data station detects a jam signal from another station, it stops transmitting for a random time and then tries again.

We distinguish two variants: with and without channel reservation. In CSMA/CA with channel reservation, the transmitter first transmits a RTS (Request to Send) for channel reservation, and waits for receiving a CTS (Clear To Send) from the destination before starting to send the data frame.

CSMA/CA is not suitable for real time communications, since it does not guarantee a upper bound for the delay before sending a data frame.

3.2 TDMA

This is a time slotted scheme used in many standards such as GSM. Accordingly with [22], TDMA (Time Division Multiple Access) is a collision-free multiple access technique whereby users share a transmission medium by being assigned and using (one at a time) time slots assigned previously.

TDMA is more suitable for real time communications, since it guarantees a upper bound delay before transmitting a data frame.

3.3 Network Analysis

To evaluate the performance of CSMA/CA and TDMA protocols on the quadrotor consensus problem, extensive simulations have been run using the network simulator NS2. As it is shown in Figures 3 and 4, it is clear that the packet drops for TDMA protocol are almost null. We attribute the packet drops shown in Figure 3 to the synchronization phase during the simulation initialization. Unlike TDMA, CSMA/CA shows a higher rate of packet drops due to its random broadcasting nature, see Figure 4.

Now, let us analyze the average end-2-end delay which gives an insight of the expected time delay on multi-quadrotor systems. It is known that in real-time applications, after a large time delay, data may become useless. Therefore it is important to analyze the performance of MAC protocols such that the multi-quadrotor system will undergo the minimal time delay.

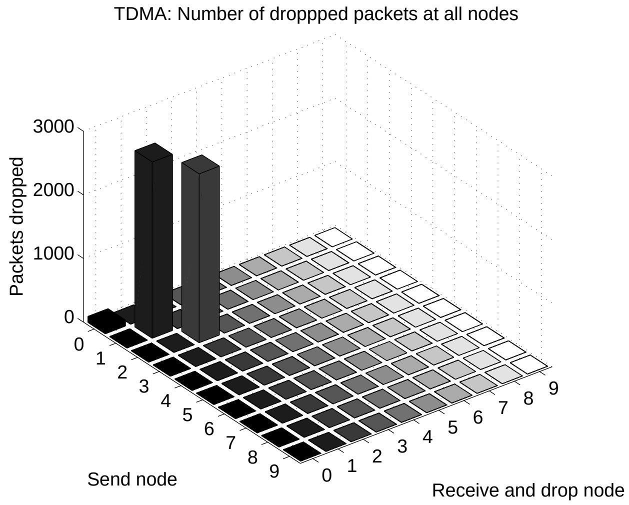

Fig. 3: Packet drop using TDMA. Simulation time = 60 sec.

On one hand, since TDMA is a time division multiple access technique to access the transmission medium, it is almost intuitively that the time delay, should show an almost constant rate. This can be confirmed by observing Figure 5. On the other hand, taking into account the packet drop rate at each quadrotor, it is expected that CSMA/CA would show a variable time delay and the maximum time delay is much higher than TDMA. The evolution of the average end-2-end time delay over time for the CSMA/CA protocol is shown in Figure 5. It is worth to mention that the end-2-end time delay has been obtained at Agent trace level, i.e. from application to application layer.

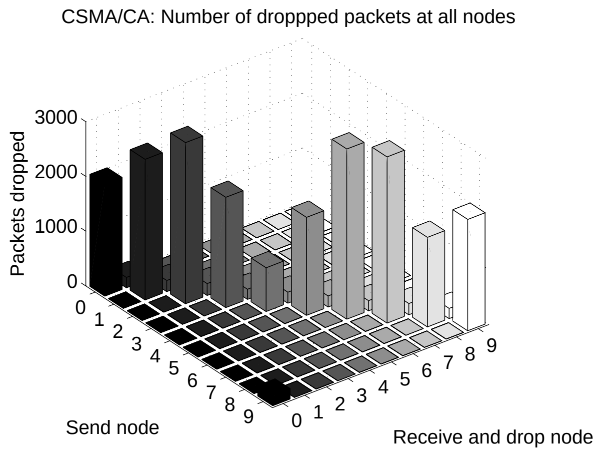

Fig. 4: Packet drop using CSMA/CA. Simulation time = 60 sec.

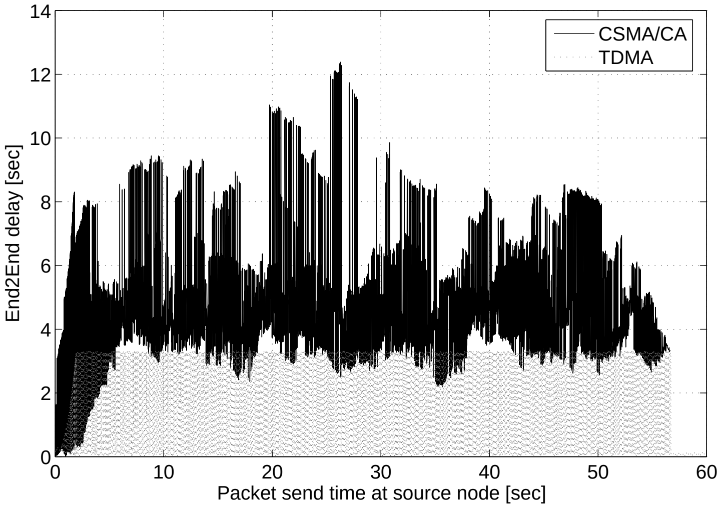

Fig. 5: End-2-End delay comparison between CSMA/CA and TDMA. Simulation time = 60 sec.

4 Quadrotor Consensus over Wireless Networks

In this section, we can introduce a Network-aware average consensus control for a multi-quadrotor system over a wireless network. By taking into account the phenomena discussed above, the packet dropout process will be considered as a source of time delays in the wireless network. As shown in [20], the end-2-end time delay τ is given by the difference $T_{dst} - T_{src}$ (time at destination and time at source, respectively) which in turn depends on the preprocessing time T_{pre}, wait time T_{wait}, transmission time T_{tx} and the post processing time T_{post}. Since the nearest neighbor approach assumes that each vehicle communicates only with immediate neighbors that are in its radio range, and assuming that a packet loss implies the re-transmission of the data that has been lost, we consider the packet dropout process, as part of the transmission time delay which has been defined as the frame time T_{frame} and the propagation time T_{prop}, more details see [20].

Then, we propose to use the following multi-quadrotor consensus control as in [23]

$$\mathbf{u}_i(t) = -\sum_{j \in \mathcal{N}_i} (\mathbf{x}_i - \mathbf{x}_j(t - \tau_{ji})) \tag{6}$$

Thus, (3) becomes

$$\mathbf{F}_i = \frac{-\sigma_{b_{1_i}}(k_{1_i}\dot{z}) - \sigma_{b_{2_i}}(k_{2_i}(\sum_{j\in\mathcal{N}_i}(z_i - z_j(t-\tau_{ji})) - z_i^d)) + 1}{\cos(\phi_i)\cos(\theta_i)} \tag{7a}$$

$$u_{\psi_i} = -\sigma_{b_{3_i}}(k_{3_i}\dot{\psi}_i) - \sigma_{b_{4_i}}\left(k_{4_i}\left(\sum_{j\in\mathcal{N}_i}(\psi_i - \psi_j(t-\tau_{ji})) - \psi_i^d\right)\right) \tag{7b}$$

$$u_{\theta_i} = -\sigma_{b_{5_i}}(k_{5_i}\dot{\theta}_i) - \sigma_{b_{6_i}}(k_{6_i}\theta_i) + \sigma_{b_{7_i}}(k_{7_i}\dot{x}_i) + \sigma_{b_{8_i}}\left(k_{8_i}\sum_{j\in\mathcal{N}_i}(x_i - x_j(t-\tau_{ji}))\right) \tag{7c}$$

$$\begin{aligned} u_{\phi_i} =& -\sigma_{b_{9_i}}(k_{9_i}\dot{\phi}_i) - \sigma_{b_{10_i}}(k_{10_i}\phi_i) - \sigma_{b_{11_i}}(k_{11_i}\dot{y}_i) \\ & - \sigma_{b_{12_i}}\left(k_{12_i}\sum\nolimits_{j\in\mathcal{N}_i}(y_i - y_j(t-\tau_{ji}))\right) \end{aligned} \tag{7d}$$

It was proved that all the states of each agent, using (2) in closed-loop system, goes to the desired values or to zero. Then for each agent $\exists$ a storage function $V_i(\mathbf{x}_i) > 0$ such that $\dot{V}_i(\mathbf{x}_i) = -S_i(\mathbf{x}_i)$ with $S_i(\mathbf{x}_i) \geq 0$. Therefore, considering the following Lyapunov function

$$V = \sum_{i=1}^{N}\sum_{j\in N}\int_{t-\tau_{ji}}^{t}\mathbf{x}_j^T(\chi)\mathbf{x}_j(\chi)d\chi + 2\sum_{i=1}^{N}V_i \tag{8}$$

this implies that,

$$\dot{V} = -2\sum_{i=1}^{N}S_i(\mathbf{x}_i) - \sum_{i=1}^{N}\sum_{j\in N_i}(\mathbf{x}_j(t-\tau_{ji}) - \mathbf{x}_i)^T(\mathbf{x}_j(t-\tau_{ji}) - \mathbf{x}_i) \tag{9}$$

From the above it follows that

$$\lim_{t\to\infty}|(\mathbf{x}_j(t-\tau_{ji}) - \mathbf{x}_i)| = 0 \tag{10}$$

From (10), it is clear that the solution of the average consensus to the average of the initial conditions depends on the network medium access algorithm, which in turn determines the values of the τ_{ji}, the transmission delay from j to i, for each quadrotor.

Figure 6 shows the performance of the average consensus considering $\tau_{ji} = \tau_{kj}$. It can be observed that the average consensus is the same than the one for the perfect communication case. The difference is that the convergence time for the equal time delay case is larger than for the perfect communication case.

Figure 7 shows the performance of the average consensus considering $\tau_{ji} \neq \tau_{kj}$. It can be observed that the solution of average consensus is different from the previous two cases: perfect communication case and equal time delays case. Based on the law of large numbers, the average of the results from a large number of simulations should be closed to the expected value. Figure 7 shows the consensus over time of the average of 1000 simulations.

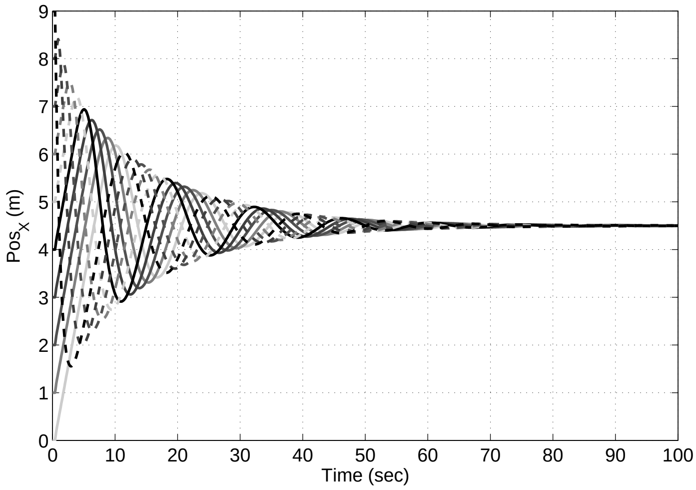

Fig. 6: Multiple quadrotor consensus with $\tau_{ji} = \tau_{kj}$

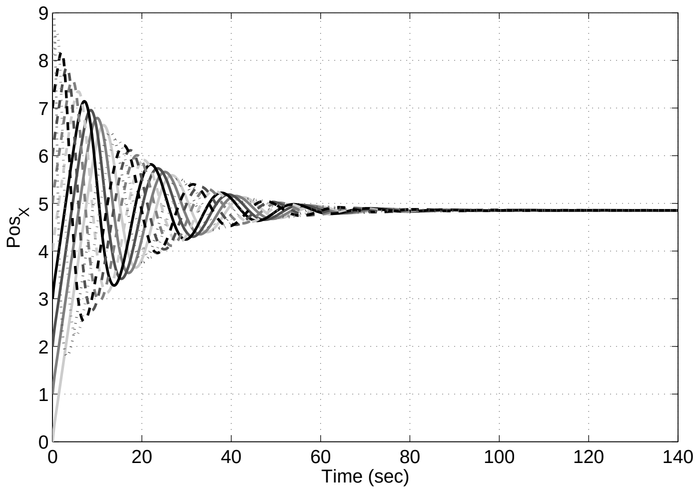

Fig. 7: Multiple quadrotor with $\tau_{ji} \neq \tau_{kj}$

5 Simulation Results

Now, let's take a look at the average consensus performance using a wireless network. The network scenario consisted of 10-quadrotors sharing information over a cyclic topology. A quadrotor application was developed, a UDP transport protocol was modified to exchange information with the quadrotor application and the MAC layer is shown in Figure 8.

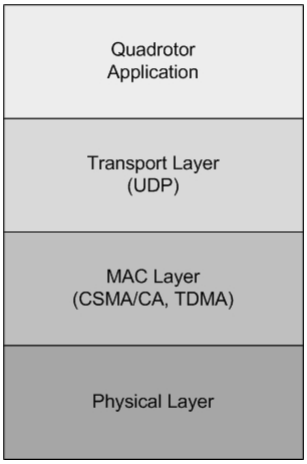

Fig. 8: Multiple quadrotor wireless network stack

The following MAC algorithms: CSMA/CA and TDMA were analyzed using the network simulator NS2. Figures 9 and 10 show the performance of the MAC protocols CSMA/CA and TDMA respectively. From Figures 9 and 10, it is possible to observe that the solution for the average consensus as well as its convergence time are affected by the network media access control algorithm.

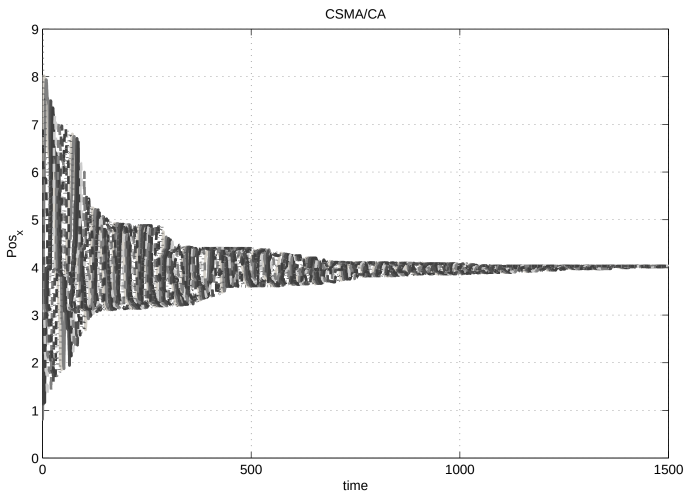

Fig. 9: Multi-agent consensus using IEEE 802.11

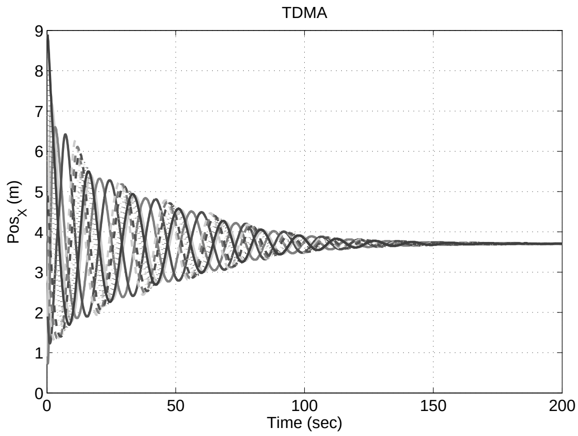

Fig. 10: Multi-agent consensus using TDMA

It can be concluded that the average consensus using a CSMA/CA protocol presents a larger convergence time due to both packet drops and time delay in the end-2-end transmission among quadrotors. Also, due to the fact that the access to the transmission medium is assigned randomly, it is evident that some quadrotors will transmit their positions to their neighbors before their counterparts. This implies that the difference between any two τ_{ji} can be large enough such that some quadrotors will evolve faster than the others. Then, the quadrotor with the smallest τ_{ji} will update its position at a highest rate than the others. Figure 11 shows the performance of the average consensus for a small platoon of 4 quadrotors using different medium access control algorithms such as: CSMA/CA, TDMA, constant time delay ($\tau_{ji} > 0$), and perfect communication.

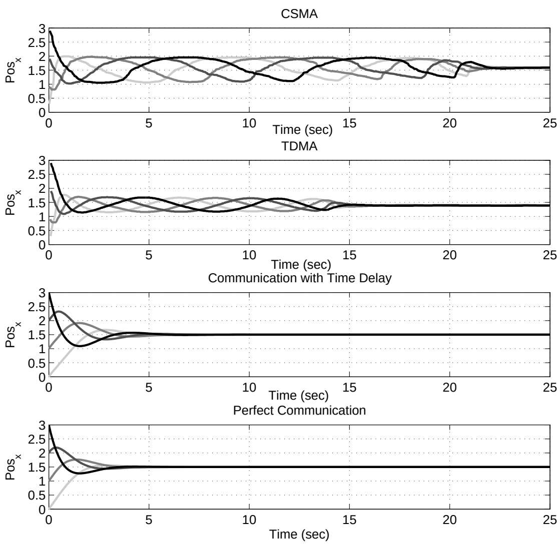

Fig. 11: Comparison of convergence time for different MAC algorithms

The simulation results are summarized in Table 1

Table 1: Performance Comparison

MAC Algorithm	Max E-2-E Time Delay	Convergence Time
CSMA/CA	~ 12	~ 1200
TDMA	~ 3.2	~ 200
Perfect Comm.	0	~ 40

In order to validate the control strategy, some experimental tests have been carried out using CSMA/CA. To simplify the experiments we focus mainly in the yaw dynamic of the helicopter. The experiment is developed as follows; first the helicopters are stabilized at hover with $\psi_{d_i} = 0$. Then, we changed manually this desired value with the control radio only for one helicopter. We begin changing ψ_d for helicopter 1, later for helicopter 2, and so on. The main result is illustrated in Figure 12. Notice from this figure, the delayed response of the second/first helicopter when it follows the first/second quadrotor. More details of the plates-formes see [12].

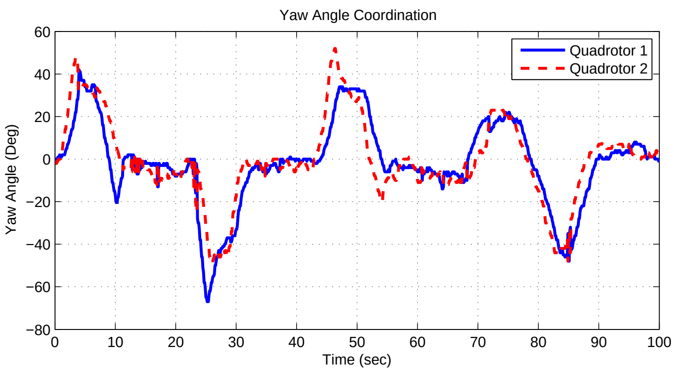

Fig. 12: Average consensus for the yaw subsystem. An external reference was given to the system in order to show the delay over the wireless network

6 Conclusions and Future Work

A nonlinear control based on saturation functions and a single integrator consensus control considering time delay for flight formation of mini rotorcraft was developed. We remark that TDMA is more suitable for real time communications than CSMA/CA, since it guarantees a upper bound delay before transmitting a data frame. CSMA/CA is less suitable for real time communications, since it does not guarantee an upper bound for the delay before sending a data frame. Extensive simulations were run in order to show the performance of the developed control scheme.

Future work in this area includes experimental tests on mini rotorcraft using real-time embedded control systems and to develop an optimized medium access control algorithm for mobile robot systems.

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