# Self-Triggered Time Coordinated Deployment Strategy for Multiple Relay UAVs to Work as a Point-to-Point Communication Bridge

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*Abstract*— **The use of multiple heterogeneous, low-cost, small Unmanned Aerial Vehicles (UAVs) as a tool in several application domains is becoming increasingly important. One critical aspect to enable the use of such vehicles is the coordination/planning system, whose task complexity increases with the number of vehicles and the communications constraints that arise due to their small size and large distances. In this work, we propose a control architecture for a platoon of relay UAVs that are independent of the coordination system. The platoon task consists in interconnecting the communication link between the possibly mobile command station and a UAV in a mission. The relays are actively driven to deploy, create a network and maintain a desired Quality-of-Service (QoS) level, defined in this paper. We present an architecture that is composed by a waypoint generator based on the network QoS and a Time Coordinated Path Following (TCPF) controller with a method to reduce the frequency of information exchange between the relay UAVs, through the use of a self-triggered control strategy. Exploiting this architecture, it is possible to plan a mission operation for a UAV without the need of considering vehicle-to-command-station communication constraints that will be satisfied by the introduction of the relay-UAVs platoon. Simulation results are provided to illustrate the efficacy of the developed strategy. The self-triggered approach results in significant reduction of information exchange between the relay UAVs, while maintaining the user desired network QoS.**

## I. INTRODUCTION

The past few decades have witnessed increasing interest in the area of motion control of autonomous vehicles. In particular, the research in the multiple heterogeneous autonomous vehicles, such as Unmanned Aerial Vehicles (UAVs) and Autonomous Underwater Vehicles (AUVs), in a joint mission is capturing the attention. The use of multiple heterogeneous, low-cost, miniature, unmanned vehicles is becoming very popular because of their large number of possible applications, including exploration, search and rescue, oceanography, etc. Considerable private and public efforts are being placed on the development and deployment of groups of networked vehicles which can interact autonomously with the environment and with one another. This interaction leads in a significant improvement of performance, robustness and efficiency. A notable example is the Ocean Observatories Initiative [1] that proposes an underwater fixed network for underwater and aerial vehicles in the Seattle bay area for oceanographic research. However, the deployment of such networks are expensive and time consuming, which prevents its utilization in every coastal region.

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The research problem addressed in this paper is motivated by the scenarios where a large number of unmanned vehicles are required to operate over large distances. In such scenarios, maintaining connectivity between the vehicles is hard to achieve. Furthermore, the miniature unmanned vehicles are equipped with low-power communication equipment which only adds to the connectivity issues. The recent work [2] highlights the communication issues in further detail.

The unmanned vehicle missions in such scenarios, usually consist of a possibly mobile command station that coordinates with one or more unmanned vehicles operating at distances beyond its communication range. The objective of this work is to devise a control strategy for the relay UAVs, in order to maintain the point-to-point connectivity between the command station and an end node (moving unmanned vehicle). To this end, we propose a scheme that actively drives an additional set of UAVs, while maintaining a desired Quality-of-Service (QoS) level, defined in this paper. Note that similar research on this direction using UAV for relay of communication can be found in [3] or [4]. In this paper, we demonstrate the use of multiple relay UAV nodes to create a single, and long distance point-to-point link between the command station and an end node. Since, the command station and the end node could be moving, we prescribe the relative positioning of the relay UAVs as desired waypoints, such that a communication link is established with the desired QoS. Furthermore, the relative spacing between the relay UAVs could change over the mission duration depending on the motion of either the command station, or the end node or both.

In order to ensure that the relay UAVs are at the designated waypoints to meet the desired QoS constraints throughout the mission duration, we impose additional temporal constraints such that the relay UAVs are tasked to arrive at the designated waypoints at the same time. As a part of the development of a mission framework that handles the communication between vehicles described above, we propose an approach to keep the vehicles formation patterns that are required in terms of keeping the desired network QoS. By actuating over the waypoints for UAVs we are able to tune the network communication variables such as connectivity bandwidth, network delay, number of hops, etc. Furthermore, in addition to the formation pattern, we impose time constraints such that the UAVs are tasked to arrive at the designated waypoints at the same time. These time constraints in conjunction with the formation pattern allows the controller to achieve a desired level of QoS even when most of the vehicles are moving. Note that it is not possible to accurately estimate the network variables during the vehicles motion if we just keep the formation between the initial and the final waypoints of the planned motion without adding time constraints.

To arrive at the QoS-based waypoints with the desired temporal constraints, we use a Self-triggered Time Coordinated Path Following (STCPF) control strategy. To this end, we make use of the self-trigger results in [16] and the time-critical coordination ideas in [6] and [7]. The STCPF strategy unfolds in the following phases. *Path Generation Phase*, where a feasible trajectory is generated for each UAV given their desired waypoint and the time of arrival. The spatial and temporal constraints of the generated trajectory is then decoupled, leading to a path to be followed by the UAV and a desired speed profile. *Path Following Phase* where a Lyapunov based nonlinear control law ensures that the UAV follows the desired reference path with a desired speed profile. *Self-triggered Time Coordination Phase* where a decentralized, self-triggered consensus controller ensures that the motion of the UAVs are synchronized such that they arrive at the designated waypoints at the same time. Additionally, the self-triggered consensus algorithm considerably reduces the frequency of transmission and controller updates on each UAV.

The paper is organized as follows. Section II presents the methodology used to address the problem of using multiple relay UAVs to work as a point-to-point communication bridge. Section III introduces the QoS algorithm for waypoint generation. Section IV presents the self-triggered time coordinated path following control strategy used to meet the desired spatial and temporal constraints. Section V validates the proposed approach through simulation results followed by conclusions in section VI.

## II. Methodology

Figure 1 shows the algorithm workflow. See also Fig. 2 and Fig. 3 that illustrate the proposed scenario addressed in this paper. The studied scenario is composed by: 1. A central station, labeled *base* acting as coordinator which could be fixed or moving. 2. A moving, surface, aerial or underwater unmanned vehicle performing a pre-planned mission labeled $endnode$. The coordinator $base$ needs to communicate with the $endnode$ moving vehicle in order to change the mission plan, recover experimental data or to get the video feed from the $endnode$. Sometimes, the $base$ has enough transmission power and/or receiving sensitivity to directly establish a communication link with the $endnode$. The reliability of this link and the communication range depends on several factors such as the transmission power, receivers sensitivity, the weather, the terrain, the antennas, frequency used, etc. Typically, the need for large transmission power and receiver antenna gain leads to heavier and larger devices. The low-cost, commercially off-the-shelf, miniature vehicles do not have the capability to carry the heavy and large

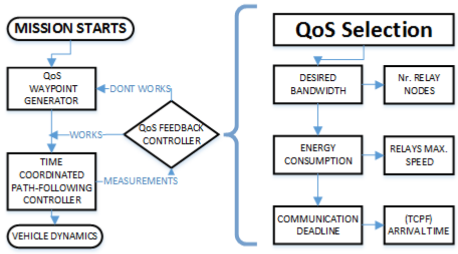


Fig. 1. Algorithm (left) and QoS selection (right) workflow.

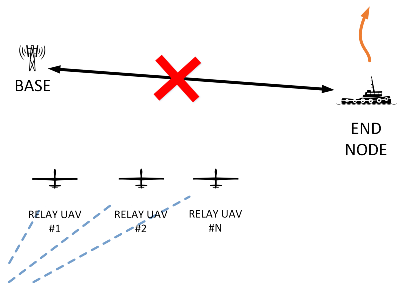


Fig. 2. First stage. Communication between the base and moving vehicle is denied and an additional set of UAVs are ready to act as relay nodes

communication devices. Hence, a pragmatic and conservative approach is adopted: limit the vehicles to operate within the communication range of the command station and/or conveniently place the relay UAV nodes to enlarge the area over which the command station can communicate. There exist previous work that model the behaviour of a relay UAV and a surface vehicle in [8]. In [2], we demonstrate the use of a feedback controller to achieve the desired QoS with one UAV. In [9] we show the use of $n$ relay UAVs to establish $n$ communication links. However, the coordinated using automatically more than one relay UAV to establish only one point-to-point communication link, while keeping the QoS has not been studied extensively. Fig. 2 shows the initial stage in the considered scenario where the communication between the base and moving vehicle is denied and an additional set of UAVs are ready to act as relay nodes. The second stage, presented in Fig. 3, describes how the relay UAVs align in order to fly towards their final destination.

## III. QoS Algorithm for Waypoint Generation

The main objective of this research is to command the relay UAVs by generating appropriate waypoints such that the desired QoS requirements are met. The waypoint generation is based on a QoS scheme that handles the trade-off between bandwidth, the energy consumption and the number of vehicles in use at the same time. In this scheme, it is the user who selects the desired QoS based on the mission and its network requirements (e.g., streaming of HD video). Then the waypoint computation acts in consequence to this selection. The system capability to adapt to the $endnode$ continuous motion depends on the frequency at which the waypoint generator is executed. The waypoint generator has to be able to run in real-time either on the system coordinator base or on the embedded computers inside the relay UAVs.

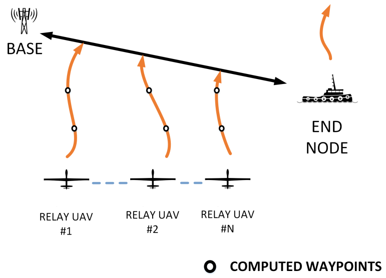


Fig. 3. Second stage. Communication between the base and moving vehicle is enabled thanks to the additional set of UAVs following the path composed by the computed waypoints.

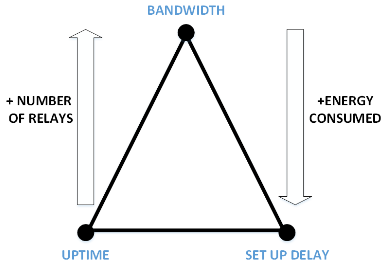


Fig. 4. QoS index diagram.

To meet these requirements the online computation has to be as accurate as possible but limiting the computation complexity. In the next subsection we explain how the energy consumption to reach a waypoint is estimated as well as the attainable bandwidth at a given location. Our approach consists in its simplicity, computing the estimated relative power consumption instead of the global one and predicting the link bandwidth based on the basic fundamental equations and relying on the actual measurements during the flight between waypoints, applied to the feedback controller, to correct the discrepancies.

### A. Energy estimation

Neglecting electronic equipment, energy consumption comes from thrust generation. This energy is converted into aerodynamic force composed by lift and drag. Thus, energy consumption depends on the motion of the UAV and in particular on its velocity. The QoS scheme proposed is able to meet energy consumption requirements by actuating on the velocity. One of the key objectives of this QoS scheme is to achieve a certain level of energy consumption without knowing much about specific UAV physics and flight parameters in advance. The energy estimation is computed using the equations shown in a previous work in [2]. We have shown the correlation between the power consumption and the UAV velocity. The propeller efficiency, that depends on the airspeed, is neglected for simplicity. Although, absolute energy consumption is difficult to calculate without the airfoil, air density and other aircraft parameters, it is well known that it grows with the third power of the velocity. It is possible to compute the *relative* power consumption based on the difference between the cruise speed and the actual speed. The computed relative power consumption can be used to bound the energy consumption and introduce it as a QoS index. To do that, we only need the UAV model cruise speed which is typically available in contrast with the aerodynamic coefficients such as the drag or lift.

QoS energy index is upper and lower bounded. The upper limit depends on the link uptime, which is the minimum estimated relay flight endurance. The lower limit is the maximum time that takes to set up the communication link. This $delay$ value is defined by the coordinator, and it is the time that takes for the UAVs to arrive to the calculated waypoints.

### B. Bandwidth estimation

Accurate bandwidth estimation is a computationally expensive task. Many external and internal variables are involved such as the specific scenario, antenna selection, weather conditions, vehicle's attitude and altitude. In general, it is possible to get a good estimation using specific software and detailed terrain or urban models. However, the computational time grows as more details are included and makes it impossible to make the calculations at high rate inside the UAVs. We propose a faster method to estimate the bandwidth. Even a simplified calculation is highly dependant on the technology used. For simulation purposes we used the information from the router TP-LINK WN-722 2.4Ghz IEEE802.11b/g/n device as the coordinator node and a similar USB device with 2dBi antenna for $endnode$. To obtain a rough estimation we need to know at least the device power transmission $P_{TX}$, the receiver sensitivity $R_X$, the receiver and transmitter antenna gains $G_{TX}$, $G_{RX}$ and the modulation method. This information is easily obtained from the device datasheets. More details on how we compute the power available could be found in a previous work in [2]. Once we know the power available, it is possible to compute the error bit rate probability in an additive white Gaussian noise channel. One of the simulated modulation schemes is the the DBPSK, quite common among the IEEE802.11b/g/n devices.

In terms of the QoS scheme, the bandwidth depends on the distance between nodes. This value is affected by the number of relays in use to build the communication bridge. Fig 4 shows the energy and bandwidth parameters trade-off in a diagram.

## IV. Self-triggered Time Coordinated Path Following

In this section, the control strategy employed to ensure coordinated arrival of the UAVs at their designated waypoints are discussed. Specifically, the Time Coordinated Path Following (TCPF) control strategy [12] is used along with the self-triggered consensus approach in order to reduce the frequency of communication between the UAVs while achieving coordination. This section extends the work presented in [5] where the Self-triggered Cooperative Path Following method is adapted to meet the desired temporal constraints such as coordinated time of arrival.

### A. Problem Formulation

Consider $N$ UAVs flying at a constant altitude modeled as a 2D fixed-wing kinematic model [14]

$$\dot{\mathbf{p}}_i(t) = R(\psi_i)\mathbf{v}_i(t) \tag{1}$$

$$\dot{R}(\psi_i) = R(\psi_i)S(\omega_i)$$

$$\omega_i = \frac{g\tan\phi_{r_i}}{v_{f_i}} \tag{2}$$

where $\mathbf{p}_i(t) \in \mathbb{R}^2$ is the 2D position of the $i^{\text{th}}$ UAV, $\mathbf{v}_i(t) = [v_{f_i}(t), 0]^T$ is the input velocity vector. The matrix $R(\psi_i) \in SO(2)$ is the rotation matrix parameterized with the yaw angle $\psi_i$. $S(\omega_i(t)) \in so(2)$ is a skew symmetric matrix with input angular velocity $\omega_i \in \mathbb{R}$. The control inputs for the vehicle are $\mathbf{u}_i(t) = [v_{f_i}, \phi_{r_i}]^T$. The yaw rate is provided by the reference roll angle $\phi_{r_i}$ through the static map given by (2) and $g$ is acceleration due to gravity. Considering $\omega_i$ to be the intermediate control input to be designed, the references for the roll command can be obtained by inverting the static map (2). The static map (2) is invertible assuming that the airspeed command of the aircraft $v_{f_i}$ is non-zero. Such an assumption is valid for a fixed-wing aircraft in flight. The Self-triggered Time Coordinated Path Following (STCPF) problem can be divided into the following subproblems:

*Problem* 1 (Path Generation). Consider the time interval $\tau \in [0, t_f]$, a known initial position $\mathbf{p}_{d_i}(0)$, and a desired waypoint $\mathbf{p}_{d_i}(t_f)$. Additionally, let the initial and final velocities denoted as $\dot{\mathbf{p}}_{d_i}(0)$ and $\dot{\mathbf{p}}_{d_i}(t_f)$ respectively, be known a priori. Feasible time trajectories $\mathbf{p}_{d_i}(\tau)$ are generated such that the boundary conditions (initial and final positions and velocities) are satisfied. The path generation problem is to construct a reference path $\mathbf{p}_{d_i}(\gamma_i)$ and a desired speed profile $v_{d_i}(\gamma_i)$ parameterized by $\gamma_i$, given the feasible time trajectory defined over the interval $[0, t_f]$. The time $t_f$ specifies the final time at which the UAVs are expected to arrive at their designated waypoints. The relation between the time variable $\tau$ and the path variable $\gamma_i$ will be made clear in the later discussion.

*Problem* 2 (Path Following). Given reference geometric path $\mathbf{p}_{d_i}(\gamma_i)$ parameterized by the path variable $\gamma_i$, with a desired speed assignment $v_{d_i}(\gamma_i)$. The path following problem is to design a feedback control law $\mathbf{u}_i(t)$ such that the path following error, $\|\mathbf{p}_i - \mathbf{p}_{d_i}(\gamma_i)\|$ converges to an arbitrary small neighborhood of the origin as $t \to \infty$. Furthermore, the UAV has to satisfy the desired speed assignment, $\|\dot{\gamma}_i - v_{d_i}(\gamma_i)\| \to 0$ as $t \to \infty$.

*Problem* 3 (Self-triggered Coordination). The objective of the self-triggered coordination controller is to design a decentralized, self-triggered control law such that the path variables $\gamma_i$ for $i = 1, \cdots, N$ of the UAVs are synchronized to achieve coordinated arrival time. Mathematically, the objective can be specified as $\|\gamma_i - \gamma_j\| \to 0$ for all $i, j = 1, \cdots, N$ and $i \neq j$ as $t \to \infty$.

In order to achieve this objective in self-triggered fashion, we propose to set the evolution of $\gamma_i$ as

$$\dot{\gamma}_i = v_{d_i}(\gamma_i) + v_r^i \tag{3}$$

where $v_r^i(t)$ is a new control variable. The control objective is to compute the corrective action $v_r^i(t) = v_r^i(t_k^i)$ for all $t \in \bigcup_{k\in\mathbb{Z}_{\geq 0}}[t_k^i, t_{k+1}^i)$ where $t_k^i$ is the time instant at which an event (transmission and controller update) occurs for agent $i$.

Additionally, another objective is to compute the next time instant $t_{k+1}^i$ at which the event should occur, thereby triggering the controller update and transmission over the network. The candidate event time can be selected as

$$t_{k+1}^i = t_k^i + \max\{\tau_k^i, b_i\} \tag{4}$$

where $b_i$ is a lower bound and hence needs to be positive in order to have a zeno free computation of next event time instant.

### B. Path Generation

Following the approach presented in [12], we choose a cubic polynomial to generate time trajectories that satisfy the boundary conditions. It is assumed that $\mathbf{p}_{d_i}(0)$, $\mathbf{p}_{d_i}(t_f)$, $\dot{\mathbf{p}}_{d_i}(0)$, $\dot{\mathbf{p}}_{d_i}(t_f)$ and $t_f$ are provided by the higher level mission controller. For each $i^{\text{th}}$ UAV, the time trajectory satisfying the boundary conditions is written as:

$$\mathbf{p}_{d_i}(\tau) = \sum_{k=0}^{3} a_k^i \tau^k \tag{5}$$

where the coefficients of the cubic polynomial are computed as,

$$\begin{aligned} a_0^i &= \mathbf{p}_{d_i}(0) \\ a_1^i &= \dot{\mathbf{p}}_{d_i}(0) \\ a_2^i &= \frac{3\mathbf{p}_{d_i}(t_f) - 3a_0 - 2a_1 t_f - \dot{\mathbf{p}}_{d_i}(t_f)t_f}{t_f^2} \\ a_3^i &= \frac{\dot{\mathbf{p}}_{d_i}(t_f) - a_1 - 2a_2 t_f}{3t_f^2} \end{aligned} \tag{6}$$

Now re-parameterizing the obtained trajectories using the path variable $\gamma_i$ and setting the time evolution of $\gamma_i$ as $\dot{\gamma}_i = 1 + v_r^i$, we have a reference spatial path $\mathbf{p}_{d_i}(\gamma_i)$ and desired speed profile $v_{d_i}(\gamma_i) = 1$. The reference path and desired speed profile forms the input to the Path Following controller discussed next.

### C. Path Following

We follow the controller presented in [13], [15] and define an error variable $\mathbf{e}_i = R^T(\psi_i)(\mathbf{p}_i - \mathbf{p}_{d_i}(\gamma_i)) + \boldsymbol{\epsilon}$, where $\epsilon = [\epsilon_1 \quad \epsilon_2]^T$ is a given small vector. The error dynamics of the path following system is given by

$$\dot{\mathbf{e}} = -S(\omega_i)\mathbf{e}_i + \Delta\mathbf{u}_i - R^T(\psi_i)\frac{\partial \mathbf{p}_{d_i}(\gamma_i)}{\partial \gamma_i}\left[1 + v_r^i\right] \tag{7}$$

where $\Delta = \begin{bmatrix} 1 & -\epsilon_2 \\ 0 & \epsilon_1 \end{bmatrix}$ and we have imposed the following condition for the dynamics of path parameter $\gamma$

$$\dot{\gamma}_i = 1 + v_r^i \tag{8}$$

where $v_r^i$ is the corrective speed actuation signal that will be viewed as an input control signal for the coordination system. Let $\epsilon$ be selected such that $\Delta$ is invertible and the term $|\frac{\partial \mathbf{p}_{d_i}}{\partial \gamma_i}|$ is bounded. Then, the following result holds.

**Theorem 1** (Path Following)**.** *Given the error dynamics for the path following system described by* (7)*, the control law*

$$\mathbf{u}_i = \Delta^{-1}\left(-K_p\mathbf{e}_i + R^T(\psi_i)\frac{\partial \mathbf{p}_{d_i}(\gamma_i)}{\partial \gamma_i}\right) \tag{9}$$

*makes the closed-loop system Input-to-State Stable (ISS) with respect to the corrective speed actuation signal* $v_r^i(t)$.

See [5] for proof.

### D. Self-triggered Coordination

Due to the limitations of space, we refer to the previous work [5] and [16] for detailed explanation of the decentralized, self-triggered consensus controller. In the following we present the event-based control law which is computed at discrete event time $t_k^i$ on each $i^{\text{th}}$ UAV. The procedure to compute the next event time $t_{k+1}^i$ at which the exchange of path variables $\gamma_i$ takes place between the relay UAVs is presented in [5].

**Theorem 2.** *Given the dynamics of the path variable* (3)*, the event-triggered, decentralized, cooperative control law*

$$v_r^i(t) = -\sum_{j\in N_i}(\gamma_i(t_k^i) - \gamma_j(t_k^i)) \tag{10}$$

*defined over* $t \in \bigcup_{k\in\mathbb{Z}_{\geq 0}}[t_k^i, t_{k+1}^i)$ *along with the triggering condition*

$$\|\tilde{q}_i(t)\| \leq \beta_i\|q_i(t)\| \tag{11}$$

*where* $\tilde{q}_i(t) = q_i(t_k^i) - q(t)$ *and* $q_i(t) = \sum_{j\in N_i}(\gamma_i - \gamma_j)$*, solves the self-triggered coordination problem and does so exponentially fast.*

At each event time $t_k^i$, UAV $i$ receives its neighbor's states $\gamma_j, j \in N_i$ and computes the control input $v_r^i(t)$ according to the equation (10). It also computes the next event time $t_{k+1}^i$ according to equation (4) using the computed average $q_i(t_k^i)$ and previously received $q_j(t_{k_{j(t)}}^j)$. Finally it transmits over the network, $q_i(t_k^i)$ which would be used by its neighbors for control computation and event generation. Consequently at each event there are $2N_i + 1$ data exchanges on each agent. The iterative algorithm used to implement the self triggered controller is given in [16] and requires that the receivers on the UAVs are always active.

## V. Simulation Results

The presented algorithm has been tested using VirtualArena Matlab toolbox [10]. The simulated scenario is the one described in Section II and in Fig. 2 and Fig. 3, where the first node labelled *base* is located at (0,70)m., and the moving vehicle labeled *end node* is at (80,90)m. The relay UAVs depart around (0,0)m. The simulation goal is to establish a link between *base* and the *end node* with a defined QoS index. The index is a way to represent the user requirement that could be more full oriented to bandwidth or to energy consumption or in between. To show the QoS index features two different indexes has been chosen:

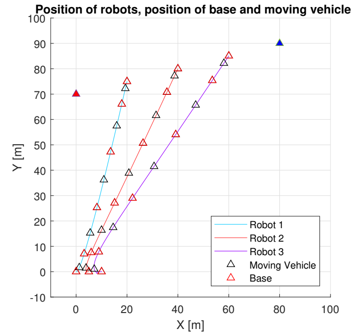


Fig. 5. Motion simulation for 3 Relay-UAVs platoon deployment

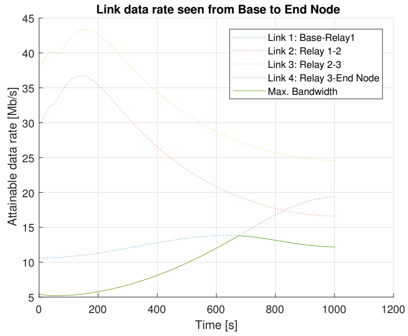


Fig. 6. Estimated link data-rate for 3 Relay-UAVs platoon deployment motion simulation. Non-dashed line is the effective attainable bandwidth

### A. QoS: Bandwidth

In this subsection we present the simulation for two different bandwidth selections. The bandwidth depends on the distance between nodes so this is affected by the number of relays. Depending on the QoS selection a different number of vehicles are launched from base. Fig. 5 and Fig. 6 show 2 vehicles in motion and the link attainable bandwidth for this set up. Fig. 7 and Fig. 8 show the same as before but using 3 vehicles. Notice the difference in data rates between the QoS indexes that use 2 or 3 vehicles to create the point-to-point link.

### B. QoS: Energy

Figure 9 and Fig. 10 present the estimated relative energy consumption as discussed in Section III. The figures show the maximum energy consumption for the QoS index for *arrival time=10s* and *arrival time=20s* . As presented before, this is part of the QoS energy trade off.

## VI. Conclusions

An algorithm for deployment of relay UAVs is presented such that the desired QoS is maintained. The proposed architecture takes into consideration scenarios where communication constraints arise and multiple relays have to be deployed in order to establish a communication link between two nodes following specific users requirements. The QoS capabilities allow the user to give preference to the link bandwidth and the flight efficiency while the motion controller is in charge of the time constraints. To probe this

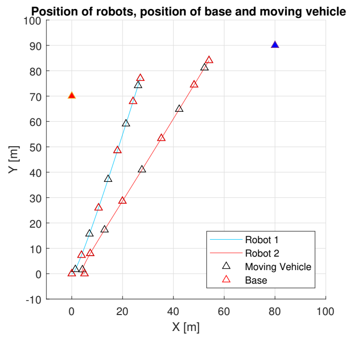


Fig. 7. Motion simulation for 2 Relay-UAVs platoon deployment

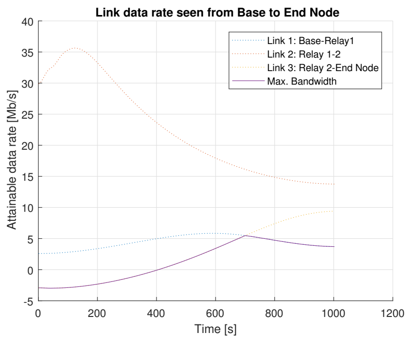


Fig. 8. Estimated link data-rate for 2 Relay-UAVs platoon deployment motion simulation. Non-dashed line is the effective attainable bandwidth

concept, simulations on a realistic scenario using the QoS capabilities have been carried out.

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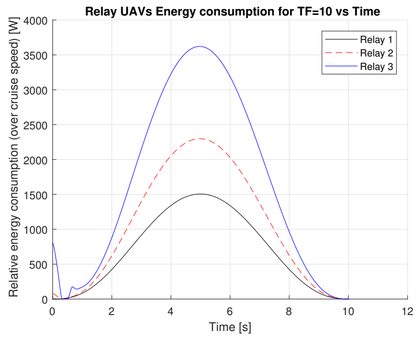


Fig. 9. Estimated relative energy consumption for *arrival time=10s.*

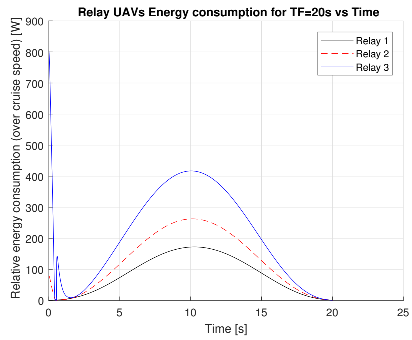


Fig. 10. Estimated relative energy consumption for *arrival time=20s.*

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