On Delay Tolerant Airborne Network Design

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Abstract. Mobility pattern of nodes in a mobile network has significant impact on the connectivity properties of the network. Due to its importance in civil and military environments, and due to the several complex issues present in this domain, one such mobile network that has drawn attention of researchers in the past few years is Airborne Networks (AN). Since the nodes in an airborne network (AN) are heterogeneous and mobile, the design of a reliable and robust AN is highly complex and challenging. This paper considers a persistent backbone based architecture for an AN where a set of Airborne Networking Platforms (ANPs) such as aircrafts, UAVs and satellites, form the backbone of the AN. As ANPs may be unable to have end-to-end paths at all times due to the limited transmission ranges of the ANPs, the AN should be delay tolerant and be able to transmit data among ANPs within a bounded time. In this paper we propose techniques to compute the minimum transmission range required by the ANPs in such delay tolerant airborne networks.

Keywords: Airborne Networks · Airborne Networking Platform · Delay tolerant networks

1 Introduction

An Airborne Network (AN) is a mobile ad-hoc network that utilizes a heterogeneous set of physical links (RF, Optical/Laser and SATCOM) to interconnect a set of terrestrial, space and highly mobile Airborne Networking Platforms (ANPs) such as satellites, aircrafts and Unmanned Aerial Vehicles (UAVs). Airborne networks can benefit many civilian applications such as air-traffic control, border patrol, and search and rescue missions. The design, development, deployment and management of a network with mobile nodes is considerably more complex and challenging than a network of static nodes. This is evident by the elusive promise of the Mobile Ad-Hoc Network (MANET) technology where despite intense research activity over the past years, mature solutions are yet to emerge [1,2]. One major challenge in the MANET environment is the unpredictable movement pattern of the mobile nodes and its impact on the network structure. In case of an AN, there exists considerable control over the movement pattern of the mobile platforms. For instance, to realize the functional goals of an AN, Air Force personnel can

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specify the controlling parameters of the network, such as the *location*, *flight path* and *speed* of the ANPs that form the backbone of the AN. Such control provides designers an opportunity to develop a topologically stable network even when the network nodes are highly mobile.

It is increasingly being recognized in the networking research community that the level of *reliability* needed for continuous operation of an AN may be difficult to achieve through *a completely mobile, infrastructure-less network* [3]. In order to enhance *reliability* and *scalability* of an AN, Milner *et al.* in [3] suggested the formation of a *backbone network* with ANPs. In order to deal with the reliability and scalability issues of an AN, we consider an architecture for an AN where a set of ANPs form the *backbone* of the AN. This set of ANPs may be viewed as *mobile base stations* with *predictable and well-structured flight paths* and the combat aircrafts on a mission as *mobile clients*.

It is desirable that such a backbone network remain connected at all times even though the topology of the network may change with the movement of the ANPs. Such continuous network connectivity can be achieved if the transmission range of the ANPs is sufficiently large. However, a large transmission range also implies high energy usage. Accordingly, one would like to know the smallest transmission range for the ANPs which ensures connectivity at all times. In [4], the authors precisely address this problem and propose techniques to find the smallest transmission range to ensure that the backbone network remains connected at all times. The authors define the *critical transmission range* (CTR) as the minimum transmission range of the ANPs to ensure that the dynamic network formed by the movement of the ANPs remains connected at all times, and present algorithms to compute the CTR when the flight paths are known.

Due to the critical nature of ANs, the ANPs may be subject to adversarial attacks such as Electromagnetic Pulse attacks or network jamming. Such attacks can impact specific geographic regions at specific times and if an ANP is within the fault region during the time of attack, it will be rendered inoperable. In [5], the authors consider the scenario where some of the AN nodes fail due to a region fault, i.e., the failed nodes are confined to a *geographic region*. The authors define a *critical transmission range in faulty scenario* (CTR_f) as the smallest transmission range necessary to ensure that the surviving nodes of the AN remain connected irrespective of the location of the fault and the time of the fault. The authors study this problem in [5] and propose techniques to compute the CTR_f.

It may be noted that in previous problems studied in [4,5] the backbone network is required to be connected at all times. Accordingly, techniques were proposed to compute CTR and CTR_f in [4,5]. However, it may not be possible to equip the transmitters of the ANPs with transmission ranges at least as large as the CTR or CTR_f. In such a scenario, the backbone network may be forced to operate in a disconnected mode for some amount of time. It is also conceivable that the data to be transmitted through the ANPs may be tolerant to some amount of delay. Hence, ANPs may not need to have end-to-end paths at all times but should be able to transmit data to each other within a bounded time.

These requirements lead us to study the problem of computation of critical transmission range in delay tolerant airborne networks. More specifically, the critical transmission range in delay tolerant network (CTR_D) is defined as the minimum transmission range necessary to ensure that every pair of nodes in the backbone network can transmit at least one bit of data with each other within a bounded time. In this paper we formulate the problem for computing CTR_D and propose techniques to compute CTR_D. To the best of our knowledge this problem has not been studied before.

The rest of the paper is organized as follows: In Sect. 2 we present the related works, in Sect. 3 the AN architecture considered in this study is detailed, in Sect. 4 the connectivity problem in delay tolerant ANs is formulated and solution techniques proposed, finally in Sect. 5 we present our experiments.

2 Related Works

Due to the Joint Aerial Layer Networking (JALN) activities of the U.S. Air Force, design of a robust and resilient ANs has received considerable attention in the networking research community in recent years. It has been noted that purely mobile ad-hoc networks (i.e., networks without infrastructure) have limitations with respect to reliability, data transmission, communication distance and scalability [3,6]. Accordingly, the authors of [3,6] have suggested the introduction of a mobile wireless backbone network where the nodes serve as mobile base stations (analogous to cellular telephony or the Internet backbone), in which topology of the dynamic backbone network can be managed through the control of movement patterns and transmission ranges of the backbone nodes.

Although there have been several studies on various aspects of mobile ad-hoc networks, most of these studies consider infrastructure-less networks, whereas the focus of this study is on ANs with a backbone infrastructure. Noted among the studies on infrastructure-less mobile ad-hoc networks is topology control in MANETs [6–9]. The goal of these studies is to assign power values to the nodes to keep the network connected while reducing energy usage. The authors of [7,8] have proposed distributed heuristics for power minimization in mobile ad-hoc networks, but have offered no guarantees on their worst case performance. Santi in [9] studied the minimum transmission range required to ensure network connectivity in mobile ad-hoc networks. He proved that the critical transmission range for connectivity (CTR) is $c\sqrt{\frac{\ln n}{\pi n}}$ for some constant c where the mobility model is obstacle free and nodes are allowed to move only within a bounded area. In these studies the mobility patterns are not known unlike the problem studied in this paper where it is assumed that the flight paths of the ANPs are known. Also, this paper studies the computation of the minimum transmission range in a delay tolerant setting that has not been studied in previous studies.

As there may be times that the networks may have to operate in a disconnected mode, the last few years have seen considerable interest in the networking research community in delay tolerant network (DTN) design [10]. The authors of [11] survey challenges in enhancing the survivability of mobile wireless networks.

It is mentioned in [11] that one of the aspects that can significantly enhance network survivability is the design of end-to-end communication in environments where the path from source to destination is not wholly available at any given instant of time. In this design, adjusting the transmit power of the nodes plays an important role. Existing DTN research mainly focuses on routing problem in DTNs [12,13]. The paper [14] provides a survey on routing algorithms for DTN. For such algorithms to be effective, every pair of nodes should be able to communicate with each other within a bounded period of time. Papers such as [15,16] have studied the problem of topology control in DTNs. In these papers, the time evolving network is modeled by a space-time graph and it is assumed that the this graph is initially connected and the problem is to find the minimum cost connected subgraph of the original graph. To the best of our knowledge, no studies exist that study the computation of the minimum transmission range of nodes in DTNs such that the time evolving network is connected over time.

3 System Model and Architecture

As mentioned previously, the level of *reliability* needed for continuous operation of an AN may be difficult to achieve through *a completely mobile, infrastructure-less network*, and if possible, a *backbone network* with ANPs should be formed to enhance reliability. It may be noted that in [5] the authors present the system model and architecture of the AN considered in this paper. We summarize that description in this section to preserve the completeness of our presentation.

In order to achieve the goal of reliability, an architecture of an AN is proposed where a set of ANPs form a backbone network and provide reliable communication services to combat aircraft on a mission. In this architecture, the nodes of the backbone networks (ANPs) may be viewed as *mobile base stations* with *predictable and well-structured flight paths* and the combat aircrafts on a mission as *mobile clients*. A schematic diagram of this architecture is shown in Fig. 1. In the diagram, the black aircrafts are the ANPs forming the infrastructure of the AN (although in Fig. 1, only aircrafts are shown as ANPs, UAVs/satellites can also be considered as ANPs). It is assumed that the ANPs follow a circular flight path. The circular flight paths of the ANPs and their coverage area (shaded spheres with ANPs at the center) are also shown in Fig. 1. Thick dashed lines indicate the communication links between the ANPs. The figure also shows three fighter aircrafts on a mission passing through a space known as an *air corridor*, where network coverage is provided by ANPs 1 through 5. As the fighter aircrafts move along their trajectories, they pass through the coverage area of multiple ANPs and there is a smooth hand-off from one ANP to another when the fighter aircrafts move from the coverage area of one ANP to that of another. At points P1, P2, P3, P4, P5 and P6 of Fig. 1, the fighter aircrafts are connected to the ANPs (4), (2, 4), (2, 3, 4), (3), (1, 3) and (1), respectively.

In this paper, it is assumed that two ANPs can communicate with each other whenever the distance between them does not exceed the specified threshold (transmission range of the on board transmitter). We are aware that in an

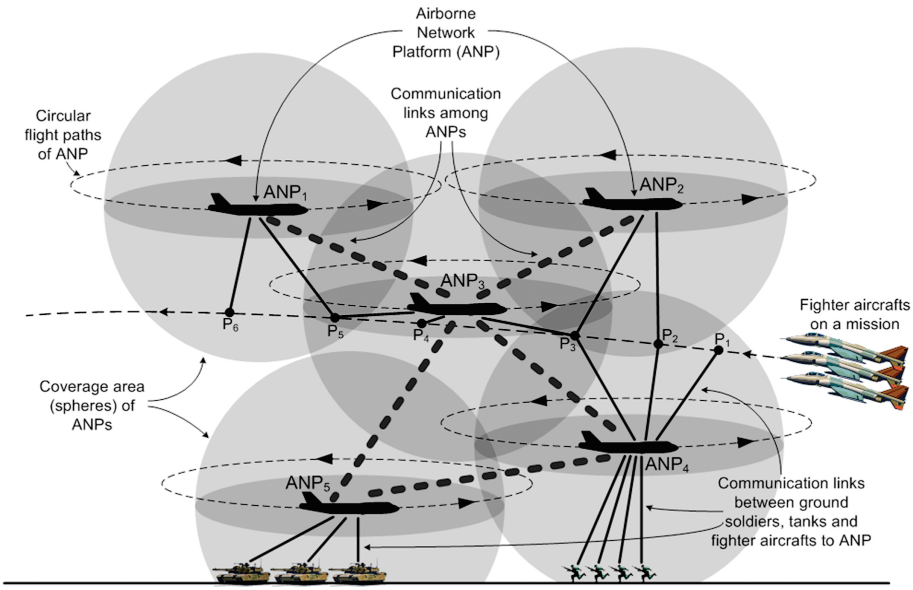

Fig. 1. A schematic view of an Airborne Network

actual airborne network deployment, successful communication between two airborne platforms does not depend only on the distance, but also on various other factors such as (i) the line of sight between the platforms [17], (ii) changes in the atmospheric channel conditions due to turbulence, clouds and scattering, (iii) the banking angle, the wing obstruction and the dead zone produced by the wake vortex of the aircraft [18] and (iv) Doppler effect. Moreover, the transmission range of a link is not a constant and is impacted by various factors, such as transmission power, receiver sensitivity, scattering loss over altitude and range, path loss over propagation range, loss due to turbulence and the transmission aperture size [18]. However, the distance between the ANPs remains an important parameter in determining whether communication between the ANPs can take place, and as the goal of this study is to understand the basic and fundamental issues of designing an AN with twin invariant properties of coverage and connectivity, such simplifying assumptions are necessary and justified. Once the fundamental issues of the problem are well understood, factors (i)–(iv) can be incorporated into the model to obtain more accurate solutions.

For simplicity of the analysis, two more assumptions are made. We assume that (i) all ANPs are flying at the same altitude thus restricting the problem to a two-dimensional plane, and (ii) they follow a circular flight path. Although these assumptions are made for this study to simplify our analysis, our techniques remain valid even when the ANP altitudes are different and the flight paths are irregular. The techniques proposed in this paper are equally applicable to any scenario as long as the flight paths are periodic and are a priori known.

4 Computation of Critical Transmission Range in Delay Tolerant Airborne Networks $\mathbf{CTR}_D$

In [4] the *critical transmission range* (CTR) was defined as the minimum transmission range of the ANPs required to ensure that the dynamic network formed by the movement of the ANPs remains connected at all times. This definition of CTR implies that although the network topology is dynamic and may change with time, if the ANPs have their transmission ranges set to CTR, the network will remain connected at all times. In [4] algorithms were proposed to compute the CTR when flight paths of the ANPs are known.

As ANPs may be susceptible to faults, specifically region based or geographically correlated faults that may render ANPs in a particular geographic region to fail, the authors of [5] introduce the notion of critical transmission range in faulty scenario (CTR_f). For a given fault region radius R, the authors of [5] define CTR_f as the smallest transmission range necessary to ensure network connectivity at all times in the presence of at most one region fault of radius R anywhere in the network. In this study it is assumed that all nodes within the fault radius R become inoperable after such a fault. The authors of [5], given region fault radius R, propose techniques to compute the CTR_f that allows the network to remain connected at all times after a region failure of radius R, irrespective of the location of the fault and the time of failure.

As noted above, the CTR and CTR_f computations of [4,5] respectively ensure that the network always remains connected in a non faulty, and faulty scenario. However, due to resource constraints of the AN, it may not be possible to equip the ANPs with radios that have coverage of radius CTR or CTR_f. Therefore, in this situation the backbone network cannot remain connected at all times. On the other hand, based on the type of data that should be transmitted between ANPs, data transmissions may be tolerant to some amount of delay. Hence, ANPs may not require to have end-to-end paths between all ANPs at all times, but instead they should be able to transmit data to each other within some limited time through intermediate nodes across different network topologies over time. In this section we investigate the problem of computation of minimum transmission range in such delay tolerant airborne networks.

We consider that the trajectories and the distance function $s_{ij}(t)$ of the network nodes are periodic over time. As a consequence, the network topologies are periodically repeated. However, periodicity is not an underlying assumption and our results can be utilized in non-periodic scenario as well as long as the node trajectories for the whole operational duration of a network are given. In [5] the authors present how to compute the *link lifetime timeline* and accordingly the network topologies caused by ANPs mobility in a time period when all inputs are given. We represent the set of topologies in a periodic cycle starting from time t_0 (current time) by the set $\mathcal{G} = \{G_1, G_2, \ldots, G_l\}$. Each network topology G_i exists for a time duration of T_i.

In Fig. 2, an example of a dynamic graph with two topologies G_1 and G_2, one periodic cycle is shown. G_1 and G_2 last for T_1 and T_2 time units respectively. It can be observed that there is no end-to-end path from A to C in either G_1

or G_2. However, A can transmit data to B in G_1, and B can forward it to C in G_2. In this situation we say that A can reach C through a temporal path with delay equal to the lifetime of G_1, i.e. T_1; and that the temporal path is completed in G_2. We define a *temporal path* from node s to d to be a set of tuples $\{(t_1, (v_1, v_2)), (t_2, (v_2, v_3)), \ldots, (t_k, (v_{k-1}, v_k))\}$ such that $v_1 = s, v_k = d$, $v_i \in V$, and for every tuple $(t_i, (v_i, v_{i+1}))$, edge (v_i, v_{i+1}) is active at time t_i, and $t_i \geq t_{i-1}$ for all $1 \leq i \leq k$. Moreover, without loss of generality, we assume that t_i corresponds to the starting time of a topology in $\mathcal{G}$. Then, the path delay is defined to be $t_k - t_0$ where t_0 is the starting time of G_1 in the first periodic cycle. We note that all path delays are computed with respect to starting point t_0 but we later show that we can modify the starting point to any time.

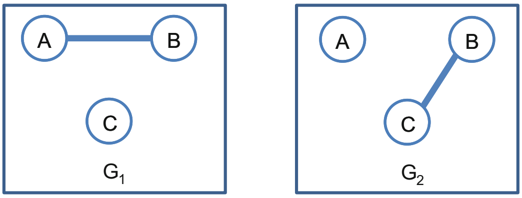

Fig. 2. A dynamic graph with two topologies G_1 and G_2

We note that the existence of a path from node i to j with some delay does not guarantee the existence of a path from j to i with the same delay. For example, in Fig. 2 the path from C to A has a delay of $T_1 + T_2$ while the path delay from A to C is equal to T_1. We say that a dynamic graph $G(t)$ is *connected with delay* D if there exists a temporal path from every node $i \in V$ to every node $j \in V \setminus \{i\}$ with delay smaller than D. It may be noted that, if the transmission range Tr is too small, ANPs may not be able to communicate with each other at all, i.e. there may be no temporal path of finite delay between the ANPs. We define *critical transmission range in delay tolerant network* (CTR_D) to be the minimum transmission range necessary to ensure that the dynamic graph is *connected with delay D*. We define *the connectivity problem in delay tolerant networks* as the problem of computation of CTR_D given the delay threshold D, and the following input parameters:

1. a set of points $\{c_1, c_2, \ldots, c_n\}$ on a two dimensional plane (representing the centers of circular flight paths),
2. a set of radii $\{r_1, r_2, \ldots, r_n\}$ representing the radii of circular flight paths,
3. a set of points $\{p_1, p_2, \ldots, p_n\}$ representing the initial locations of the platforms, and
4. a set of velocities $\{v_1, v_2, \ldots, v_n\}$ representing the speeds of the platforms

In order to find the value of CTR_D, first we explain a technique to check whether a transmission range Tr is adequate for having a connected dynamic network with delay D. First, we determine the set of events ($L(tr)$) when the state of a link changes from active to inactive (and vice-versa), when the transmission range is set to Tr. The technique to build the set $L(tr)$ was proposed in [5] and we restate it here for the sake of completeness. From the specified input parameters (1) through (4) we first determine the lifetime (active/inactive intervals) of every link between every pair of nodes i and j by comparing $s_{ij}(t)$ with Tr and finding the time points that the state of a link changes. Let $L(Tr) = \{e_1, e_2, \ldots, e_l\}$ denote the set of events, or e_i's, when the state of a link changes when transmission range is Tr; let $L(tr)$ be sorted in increasing order of the time of the events. Hence, between two consecutive events e_i and e_{i+1} that occur at times t_i and t_{i+1} the set of active links is unchanged. Algorithm 1 summarizes this technique of computing $L(Tr)$.

Algorithm 1. Link Lifetime Computation

Input: (i) a set of points $\{c_1, c_2, \ldots, c_n\}$ representing the centers of circular flight paths, (ii) a set of radii $\{r_1, r_2, \ldots, r_n\}$ representing the radii of circular flight paths, (iii) a set of points $\{p_1, p_2, \ldots, p_n\}$ representing the initial locations of the platforms, (iv) a set of velocities $\{v_1, v_2, \ldots, v_n\}$ representing the speeds of the platforms.
Output: $L(Tr)$: an ordered set of events that the state of a link changes from active to inactive or inactive to active.

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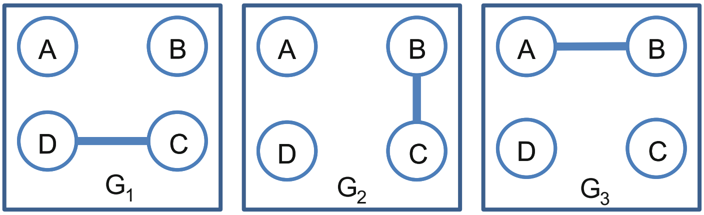
L(Tr) ← ∅
for all pairs i, j do
    Compute l to be the set of time points t such that s_ij(t) = Tr (using equation
    (5) of [5]) over a period of time, to find the instances of times t where the state of
    the link (i, j) changes. If s_ij(t) = Tr and is s_ij(t) increasing at t, it implies that
    the link dies at t, and if s_ij(t) decreasing at t, it implies that the link becomes
    active at t.
    for all l_k ∈ l do
        Find the position of l_k in L(Tr) using binary search and Add the event into
        L(Tr). (L(Tr) is sorted in increasing order)
    end for
end for
```

It has been shown in [5] that the time complexity of Algorithm 1 is $O(n^4)$, and $|L(Tr)| = O(n^2)$. Before describing the rest of the technique to check whether a transmission range Tr is adequate for having a connected dynamic network with delay D, we propose the following observation:

Observation 1. *For a given transmission range Tr, there is a temporal path from every node u to every node v with finite delay iff the superimposed graph $G_c = \{V, \bigcup_{i=1}^{l} E_i\}$, where E_i is the set of edges in G_i, is connected.*

Although a transmission range Tr may be enough to result in a connected superimposed graph G_c, it may not be sufficient for the existence of a temporal path between every pair of nodes with delay smaller than a threshold D even if D is as large as $\sum_{i=1}^{l-1} T_i$. Figure 3 depicts an AN with three topologies in one period.



(a) (b) (c)

Fig. 3. A dynamic graph with three topologies G_1, G_2 and G_3

It can be observed that A cannot have a temporal path from A to D in the first period. Actually the fastest path includes edges (A, B) in G_3 in first period, (B, C) in G_2 in the second period and (C, D) in G_1 in the third period. Therefore, the path delay is $2(T_1+T_2+T_3)$. Generally, in the worst case in every period just a subpath (a set of consecutive edges) in one topology is used and therefore the maximum delay of a temporal path will be $D_{max} = (l-1)\sum_{i=1}^{l} T_i$. Hence, if $D \geq D_{max}$, examining the connectivity of G_c is enough to decide whether for a transmission range there exists a temporal path of delay smaller than D between every pair of nodes in the dynamic network.

We now present an algorithm that checks for a given value of transmission range Tr, whether a network is connected with delay D where $D < D_{max}$. Let $N(u)$ denote the set of nodes that are reachable from $u \in V$ with delay smaller than D. Initially $N(u) = \{u\}$. The algorithm starts by computing the connected components in every topology G_i. Let $C_i = \{C_{i,1}, C_{i,2}, \ldots C_{i,q_i}\}$ represent the set of connected components in G_i where $C_{i,j}$ is the set of nodes in the jth component of G_i, and $q_i = |C_i|$. Let g and h be the quotient and remainder of $\frac{D}{\sum_{i=1}^{l} T_i}$ respectively, and $t_0 + h$ is the time where the network topology is G_p for a p, $1 \leq p \leq l$. Therefore, the topologies in time duration t_0 to $t_0 + D$ includes G_1 to G_l for g number of cycles and G_1 to G_p in the last periodic cycle. Starting from the first topology G_1 in the first period, in each topology G_i, if a node v is in the same connected component with a node $w \in N(u)$, then v can be reachable from u through a temporal path which is completed in G_i; hence, $N(u)$ is updated to $N(u) \cup (\bigcup_{k:N(u)\cap C_{i,k}\neq\emptyset} C_{i,k})$. In this step the algorithm goes through all the topologies from t_0 to $t_0 + D$. In the end, if $N(u) = V$ for all $u \in V$, then the transmission range Tr is sufficient for having a connected network with delay D. In Algorithm 2 the steps of checking the connectivity of a dynamic graph with delay D is presented.

As shown in [5] the number of topologies, l in a single period of the dynamic topology is $O(n^2)$. Thus, the computation of the connected components of a graph $G_i = (V, E_i)$ using either breadth-first search or depth-first search requires a time complexity of $O(|V|+|E_i|) = O(n^2)$. Hence, Step 2–4 of Algorithm 2 takes $O(n^4)$. It may be noted that this algorithm is used for the case when $D < (l-1)\sum_{i=1}^{l} T_i$. Therefore, the number of periods $g < l - 1$, and $g = O(n^2)$. Computation of

Algorithm 2. Checking Connectivity of Airborne Network with delay D

Input: $\mathcal{G}(t) = \{G_1, G_2, \ldots, G_l\}$ and delay threshold D
Output: *true* if dynamic graph $\mathcal{G}(t)$ is connected with delay D; otherwise *false*.

1: Initialize $N(u) = \{u\}$ for every $u \in V$
2: **for all** topologies $G_i, 1 \le i \le l$
3:    Compute $C_i = \{C_{i,1}, C_{i,2}, \ldots C_{i,q_i}\}$, the set of connected components of G_i
4: **for all** periods 1 to g
5:    **for all** topologies $G_i, 1 \le i \le l$
6:       **for all** node $u \in V$
7:          $N(u) \leftarrow N(u) \cup (\bigcup_{k: N(u) \cap C_{i,k} \neq \emptyset} C_{i,k})$
8: **for all** topologies $G_i, 1 \le i \le p$ (the topologies in the last period)
9:    **for all** node $u \in V$
10:       $N(u) \leftarrow N(u) \cup (\bigcup_{k: N(u) \cap C_{i,k} \neq \emptyset} C_{i,k})$
11: **for all** node $u \in V$
12:    **if** $N(u) \neq V$, **return** $false$
13: **return** $true$

Step 5 is also $O(n^2)$ since $|N(u)|$ and the total size of all components in G_i is $O(n)$. Overall, it can be concluded that the time complexity of Algorithm 2 is $O(n^7)$.

Additionally, as all the delays are computed with respect to t_0, we can easily extend this technique to any t_i, by repeating Algorithm 2 for every $t_i, 1 \le i \le l$ where t_i is the starting time of topology G_i. Thus, this extension increases the complexity by a factor of $l = O(n^2)$.

Finally, similar to the computation of CTR and CTR_f in [4,5], in order to compute CTR_D a binary search can be carried out within the range $0 - Tr_{max}$ to determine the smallest transmission range that will ensure the AN is connected with delay D during the entire operational time. The binary search adds a factor of $\log Tr_{max}$ to the complexity of Algorithm 2 to compute CTR_D.

5 Simulations

The goal of our simulation is to compare critical transmission ranges in different scenarios of non faulty (CTR), faulty (CTR_f) and delay tolerant (CTR_D) to investigate the impact of various parameters, such as the number of ANPs, the region radius and delay, on the critical transmission range. In our simulation environment, the deployment area considered was a 1000×1000 square mile area. The centers of the orbits of the ANPs were chosen randomly in such a way that the orbits did not intersect with each other. In our simulation, we assumed that all the ANPs move at the same angular speed of $\omega = 20\,\text{rad/h}$. Hence a period length is 0.1π h. One interesting point to note is that, in this environment where all the ANPs are moving at the same angular speed on circular paths, the value of CTR is independent of the speed of movement of the ANPs. This is true because changing the angular speed ω effects just the time at which the events take place, such as when a link becomes active or inactive. If we view the

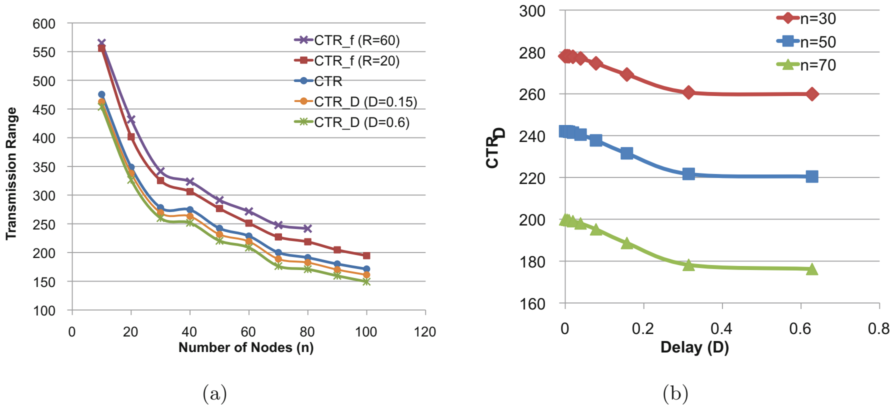


Fig. 4. (a) Transmission Range vs. Number of Nodes; (b) Transmission Range (CTR_D) vs. Delay

dynamic topology of the backbone network over one time period as a collection of topologies $\mathcal{G} = \{G_1, G_2, \ldots, G_l\}$, where G_i morphs into $G_{i+1}, 1 \leq i \leq l$ at some time, by increasing or decreasing the angular speed of all ANPs, we just make the transitions from G_i to G_{i+1} faster or slower, without changing the topology set $\mathcal{G}$. Similarly, the set of ANPs that fail due to failure of a region at a certain time remains unchanged.

In our first set of experiments we compute CTR, CTR_f when $R = 20, 60$, and CTR_D when $D = 0.5\ \textit{period}, 2\ \textit{period}$ for different values of number of nodes, n. Figure 4(a) depicts the result of these experiments. In these experiments, for each value of n we conducted 30 experiments and the results were averaged over the 30 different random initial setups. We set $\textit{orbit radius} = 10$. We observed that as expected, an increase in the number of nodes results in a decrease in CTR, CTR_f and CTR_D. Moreover, $\text{CTR}_D \leq \text{CTR} \leq \text{CTR}_f$ for all instances. In all of the experiments, we computed CTR_D with respect to all times (corresponding to beginning of a new topology) and not just t_0.

In the second set of experiments, we conducted experiments to investigate the impact of delay D on the value of CTR_D. Figure 4(b) depicts the results. We observe that when value of delay D is zero the value of CTR_D is equal to CTR and by increasing delay, CTR_D decreases and the interesting observation is that when delay becomes greater than 2 *period* the decrease in the value of CTR_D is unnoticeable or even zero.

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