Improving the Performance of Challenged Networks with Controlled Mobility

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Abstract. In this work, we investigate the application of an adapted controlled mobility strategy on self-propelling nodes, which could efficiently provide network resource to users scattered on a designated area. We design a virtual force-based controlled mobility scheme, named VFPc, and evaluate its ability to be jointly used with a dual packet-forwarding and epidemic routing protocol. In particular, we study the possibility for end-users to achieve synchronous communications at given times of the considered scenarios. On this basis, we study the delay distribution for such user traffic and show the advantages of VFPc compared to other packet-forwarding and packet-replication schemes, and highlight that VFPc-enabled applications could take benefit of both schemes to yield a better user experience, despite challenging network conditions.

Keywords: Controlled mobility · Virtual forces · MANET · Challenged networks · DTN · Unmanned aerial vehicles · Disaster communications

1 Introduction

Over the last 15 years, the notion of ubiquitous network access got closer to reality. As an illustration, by that time, the worldwide Internet penetration rate has grown 7 times, reaching 43% in 2015 [1]. Yet, this encouraging key performance indicator should not conceal the acute challenges still posed by the current need to greatly improve access to network infrastructure in many unconnected or ill-connected territories. Although the reasons for this imperfect network coverage may differ, with various issues and constraints met in either rural areas, remote zones or emerging countries, alternate communication resources need to be deployed on site to grant network access. A similar problem arises in the case of disasters which may leave the existing networks impaired at a time when communications are greatly needed by the rescue, response and restoration teams. To this end, various rapid deployment communication systems were proposed, often relying on different types of terrestrial, aerial and satellite network segments [2]. Moreover, the principles of Mobile Ad Hoc Networks (MANETs) [3] have often been adopted in these contexts [4], since they

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can forgo the time-consuming, staff-demanding and potentially costly roll-out of a surrogate cellular network infrastructure. Further, MANETs allow devices to form temporary and self-organized networks in dynamic topologies, where multi-hop communications are used to extend the inherently limited range of wireless transmissions. Yet, in the context of challenged networks [6] with high node mobility, low node density and other detrimental issues, the performance of MANETs can be severely hindered by the scarcity of network connectivity and subsequent link disruptions, which in turn increase packet losses [5]. In contrast, Delay/Disruption Tolerant Network (DTN) techniques were designed to handle packet delivery in case of intermittent connectivity found in challenged networks. Moreover, while MANETs use synchronous routing schemes based on the determination of an end-to-end path, DTN schemes on the other hand rely on the asynchronous store-carry-and-forward principles [7] wherein a network node buffers and carries incoming packets as it moves. Further, among the proposed DTN routing strategies, two specific directions were abundantly explored:

– *Packet-forwarding*, which, often combined with modified synchronous protocols to support longer delays (e.g. Deep-Space Transport Protocol (DS-TP) or TP-Planet [5]), allows better packet delivery with respect to MANET performance.
– *Epidemic approaches* enable a node to transmit copies of incoming packets to nodes it gets in contact with. As a result, multiple replications of a specific packet may exist in the network at the same time, increasing the chances for this packet to reach its destination. Yet, a systematic packet replication at each contact opportunity incurs a significant resource consumption. As a result, several solutions (e.g. MaxProp [9], RAPID [10] and Spray and Wait [8]) were proposed to keep packet replication as low as possible.

In this regard, due to the unpredictable nature of most intermittently connected networks, traditional DTN schemes fail to fully ensure consistent network performance gains with respect to multiple key routing metrics such as packet delivery, delay, overhead and resource consumption. This observation has been referred to as the incidental effect [10] of existing DTN schemes. To overcome this limitation, the concept of controlled mobility [16] has recently been explored, bringing a new perspective on network node mobility, which was until then mainly considered as an unavoidable nuisance requiring mitigation. In contrast, controlled mobility enforces deployed network protocols with the ability to put nodes in motion and direct them where they can help increase the overall network performance. Some forms of controlled mobility mechanisms have been notably studied in the context of DTNs, where specific nodes may be used as message ferries to enhance connectivity in networks with sparsely deployed nodes [16]. Likewise, wireless sensor networks may benefit from data sinks with controlled mobility for various performance aspects, such as network lifetime increase [17]. In this work, we particularly focus on swarming principles, a distributed form of controlled mobility for which local node interaction can engender desirable emergent behaviors [18]. In effect, swarming mechanisms give network nodes the ability to cooperatively readjust their movements thanks to the exchange of local information and to collectively achieve a given spatial organization. In this regard, although swarming mechanisms generally require a large number of mobile nodes to complete pattern formations such as grids and lattices [13], specific strategies can achieve chain formations with a limited number of nodes, which is a useful property in network deployments, where the number of nodes is often constrained. Thus, several works studied chain formations with probabilistic finite state machine [19] and evolutionary robotics techniques [20].

In our previous studies, we investigated a third approach, for which local information exchange is based on virtual force principles [14,15]. We notably presented in [15] the Virtual Force Protocol (VFP), allowing mobile nodes, and in particular unmanned aerial vehicles (UAVs), to form communication chains and provide network connectivity in the context of disaster relief operations. We assessed VFP performance and notably showed that a peak efficiency was obtained with a limited set of nodes, which confirmed its interest in network deployments where the number of nodes is constrained. Yet, the performance gain from the use of a simple MANET protocol to a joint use of MANET and VFP, however significant, could not exceed a relatively low threshold of about 40%, in terms of Packet Delivery Ratio (PDR).

In this work, we seek to overcome this PDR limitation while keeping end-to-end delays as low as possible. To this end, our main contribution can be summarized as follows: we give our VFP-based strategy, which we here name VFPc, the ability to work jointly with a DTN epidemic scheme, with the objective to thoroughly improve packet delivery. We also design a cross-layer framework that allows switching from packet-replication to packet forwarding (and reciprocally), based on the context given by VFPc to the upper layer routing components, in terms of whether a VFP communication chain is established or not. That way, end-users can benefit from synchronous communications when a VFP chain connects the traffic endpoints. Otherwise, the network autonomously falls back to asynchronous communications. The rest of this paper is organized as follows: Sect. 2 presents the disaster relief scenario which gives the context of this study. Section 3 details the design choices made for our VFPc strategy and other schemes used as comparison references. The performance of VFPc is then evaluated along with the other schemes, in terms of PDR and end-to-end delay, in Sect. 4, and we finally conclude in Sect. 5.

2 Scenario

In the context of this study, we envision a scenario where a rapid deployment communication system is required to provide network coverage on a zone Z_e where network access is non-existent or temporarily impaired. To this end, our system encompasses the following nodes, as illustrated by Fig. 1:

- *Traffic nodes* are regular end-user devices which, like the other nodes, support the VFPc scheme in order to cooperate with the rest of the network. Two such

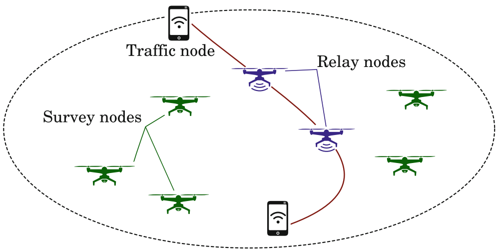

Fig. 1. A representative network deployment in the considered scenario.

nodes are assumed to move randomly within Z_e, respectively acting as source and destination of all user traffic during the considered case flow.
- *Survey nodes* explore Z_e, exchange information with other nodes in radio range and store their location for future use and dissemination in the network.
- *Relay nodes* are initially survey nodes which change their function at given times to become part the set of intermediate nodes in the multihop communication chain between the traffic nodes. When not needed anymore in the chain, relay nodes revert to their former survey type.

3 VFP Protocol Design

3.1 A Force-Based System

Our VFPc scheme implements a virtual force-based distributed system, VFP [14,15], which is used to control node mobility so as to create and maintain a wireless multi-hop communication chain between any traffic (source, destination) pair. Further, VFP defines a beacon message which is regularly broadcast 1-hop away by each node in the network. VFP beacons contain various information such as the emitting node coordinates and velocity vector, whether it belongs to a communication chain and in that case which intermediate nodes are preceding and following in the chain. It additionally encompasses a list of nodes previously discovered, also with relevant information. This local distribution of information is a pivotal mechanism for network nodes to quantify the forces exerted by neighboring nodes, reassess their own subsequent acceleration and velocity vectors, move accordingly, and take part to the relay node election process [15]. As illustrated by Fig. 2 (left), relay nodes in a communication chain (nodes P and N in the given example) are subjected to interaction and alignment forces. To calculate both forces, nodes use received VFP beacon information differently:

- Interaction forces [14], which encompass three repulsive, friction and attractive components, are exerted by the node's predecessor in the chain (i.e. N and P are subjected to interaction forces from respectively P and S in the given example). Depending on the distance with its predecessor, a node can be

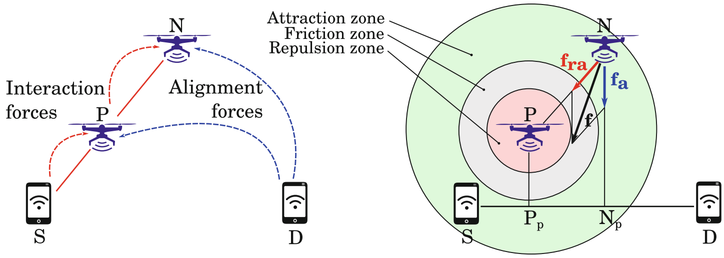

Fig. 2. (left) Principles of virtual forces applied on nodes P and N in a communication chain, (right) detailed forces on N (note that friction $\mathbf{f_{fr}}$ is non-existent in this case). (Color figure online)

located in a virtual repulsion, friction or attraction zone, delineated by the red, grey and green areas in Fig. 2 (right). In this study, we select a repulsion-attraction intensity profile such that $f_{ra} = I$ in the repulsion zone, $f_{ra} = -I$ in the attraction zone and $f_{ra} = 0$ elsewhere. Further, the repulsion-attraction force is used to move the node within a given relative distance from its predecessor, while the friction force $\mathbf{f_{fr}}$ enables smooth decelerations and allows avoiding undesirable oscillating movement effects [14]. These forces are calculated on the basis of 1-hop information received from the predecessor's beacons.

– In contrast, alignment forces [15] can be calculated by a relay node as soon as it learns the position of the traffic source and destination nodes (S and D in the example of Fig. 2). This force steers relay nodes towards line (SD), and ultimately tends to generate a straight line topology for the communication chain. In the example of Fig. 2 (right), the alignment force $\mathbf{f_a}$ tends to steer N towards its projection N_p on line (SD). If N_p was closer from P_p to S, $\mathbf{f_a}$ would be directed towards the symmetric point of N_p about P_p on (SD). That way, the alignment force also helps reordering chains if a relay node is not correctly located with respect to its predecessor and successor in the chain.

3.2 A Cross-Layer Framework

Figure 3 gives an architectural representation of the dual routing stack made of a packet-forwarding scheme (the synchronous stack) and a packet-replication scheme (the asynchronous stack) hosted on each node. It also outlines how three VFP entities interact with the other main components involved both in network traffic transmission as well as in node mobility control:

– The *mobility controller* retrieves information such as coordinates and velocity vectors from the node Inertial Measurement Unit (IMU) and various sensors via the Autopilot application. This entity also performs the calculation of the force system exerted on the node based on available local information and sends the Autopilot the updated measures (e.g. under the form of a velocity vector or a waypoint).

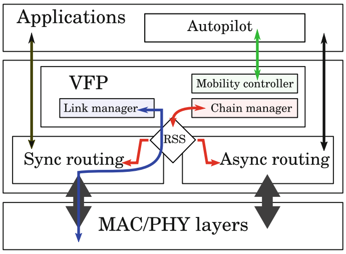

Fig. 3. Representation of the cross-layer framework. (Color figure online)

- The *link manager* is in charge to periodically build and emit VFP beacons as well as receive and store beacons from neighboring nodes. As shown by the blue arrows, VFP beacons only rely on 1-hop broadcasts provided by the synchronous scheme and don't require any DTN persistence.
- The *chain manager* works together with a selection mechanism (illustrated by the red arrows in Fig. 3) which allows triggering the relevant routing stack depending on the VFP status of the node: if this later does not belong to an established VFP chain whose destination matches the considered user traffic destination, then the corresponding packets are handled by the DTN-based asynchronous stack. Otherwise, it is known the node has an available multi-hop route via its successor in the chain to the destination and the selection mechanism lets the synchronous stack handle packet forwarding on a hop-by-hop basis.

3.3 Implementation Aspects

Although the outlined framework may allow the use of multiple routing schemes, specific deployment choices were required to allow a rigorous performance evaluation of VFPc. Because of its well-documented properties, the epidemic protocol [12] was therefore selected for deployment as packet-replication scheme within the cross-layer framework. This DTN protocol exhibits a simple opportunistic flooding-based design, with the use of a dedicated beacon to inform nodes of contact opportunities with neighboring nodes, as well as of another specific mechanism, the *summary vector exchange*, which allows two nodes to exchange their disjoint packets during contacts. Moreover, we implemented the Routing Stack Selector (RSS) shown by Fig. 3 as well as a simple forwarding scheme in the same component. Basically, when an incoming packet needs processing, the component requests the VFP status of the node, and if applicable, the identifier of its successor in the chain. If applicable, the packet is immediately forwarded to the successor. Otherwise, the packet is passed to the epidemic protocol and will be kept into persistent storage for further transmission, when a contact opportunity with a neighboring node arises.

On this basis, we designed seven routing strategies, as Fig. 4 shows. The first six schemes only partially use our framework components. The **RWP1** scheme

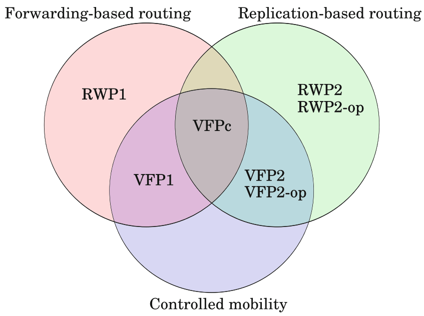

Fig. 4. Overview of the implemented schemes, ordered by function support.

exclusively relies on Random Waypoint Mobility (RWP) and not on virtual force-based controlled mobility. Besides, it only supports a MANET forwarding-based routing. We also study two other RWP-based schemes which on the opposite only support the epidemic protocol: while **RWP2** uses a regular epidemic stack with default values, **RWP2-op** lowers the period of packet list exchange between two neighboring nodes by setting $HostRecentPeriod = 1$ s (instead of 10 s by default) [12]. Hence, the use of this later scheme should incur a faster transmission of epidemic packets during contacts (i.e. when nodes are in direct radio range and able to exchange their list of stored epidemic packets to determine which packets should be transmitted). We also consider the **VFP1** scheme, which supports VFP controlled mobility and which relies on a MANET forwarding-based routing, but never on the epidemic routing. As a result, the user traffic in only transmitted when valid end-to-end routes are established and is dropped otherwise. We then implemented two VFP-based schemes which only rely on the epidemic stack: whereas **VFP2** uses the epidemic routing with default values, **VFP2-op** employs optimized values, with the aforementioned expected benefits. The last strategy, **VFPc**, supports all the features offered by our framework: the VFP component controls node mobility when applicable, and the user traffic is contextually passed to the epidemic or the forwarding scheme, depending on whether the considered node belongs to an established communication chain. It is worth noting that VFPc uses the default epidemic parameter valuation.

4 Performance Evaluation

4.1 Simulation Parameters

The simulation parameters were chosen as closely as possible as those described in our previous work [15]. Table 1 summarizes the values of the key parameters of our simulation setup, which uses the network simulator ns-3.23.

The node number, initial positions and mobility patterns are given in Table 1. All nodes use IEEE 802.11b/g communication links with High-Rate

Table 1. Main simulation parameters

Nodes	Exploration zone $Z_e = 1000$ m $\times$ 1000 m, 2 traffic nodes, N (survey + relay) nodes, $N = 15$ or $1 \leq N \leq 30$	
Mobility patterns	Traffic nodes	Position initially uniformly distributed on Z_e, RWP, velocity $\in [0.25, 1]$ m/s
	Survey nodes	Position initially at center of Z_e, RWP, velocity $\in [5, 10]$ m/s
	Relay nodes	VFP-based mobility, velocity $\in [0, 10]$ m/s
Network	802.11b/g, HR-DSSS at 11 Mb/s, radio range = 100 m constant speed propagation delay model	
VFPc protocol	Beacon emission interval = 1 s, interaction forces $\mathbf{f_{ra}}$ and $\mathbf{f_{fr}}$ configured as in [14], Alignment force $\mathbf{f_a}$ valued as in [15]	
Routing	MANET	OLSR with default values [11]
	DTN	Epidemic protocol [12]
User traffic	CBR bitrate = 10 Kb/s, CBR packet size = 512 B	

Direct Sequence Spread Spectrum (HR-DSSS) at 11 Mb/s, whose communication range is set to 100 m and radio propagation is assumed lossless. Moreover, the MANET routing is supported by the Optimized Link State Routing protocol (OLSR) [11] for the non-crosslayer schemes that use the packet-forwarding stack (i.e. the RWP1 and VFP1 strategies). In contrast and as previously mentioned in Sect. 3.3, the packet-forwarding component of VFPc relies on a VFP-based simplified hop-by-hop routing. With respect to the force-based controlled mobility, Table 1 refers to our previous works [14,15] which provide a detailed justification of the chosen values for respectively the interaction forces $\mathbf{f_i}$ and the alignment forces $\mathbf{f_a}$. Moreover, the user traffic is modelled with a Constant Bitrate (CBR) flow at 10 Kb/s, which is assumed sufficient in the context of the considered scenario to convey important and potentially delay-tolerant traffic, such as UAV telemetry or payload sensor data. Note that the case of larger bitrates was studied in [14]. Further, each point of Figs. 5, 6 and 7 are respectively averaged over 2000 and 10000 independent simulations of 900 s each. On that note, errors bars are shown in all figures and are based on a confidence level of 95%.

Results are analyzed in the rest of this section, and are based on two performance metrics: the Packet Delivery Ratio (PDR) relates to the user traffic between both traffic nodes. Then, the end-to-end delay is defined here from source to destination traffic node, for the same user traffic. We additionally examine the Cumulative Distribution Function (CDF) of this delay.

4.2 Simulation Results

We first took interest in how the considered schemes behave with an increasing number of nodes. We followed a similar approach as taken in our previous study [15] regarding the performance of VFP1 and RWP1 with respect to PDR and end-to-end delay, this time using those results as a comparison basis to

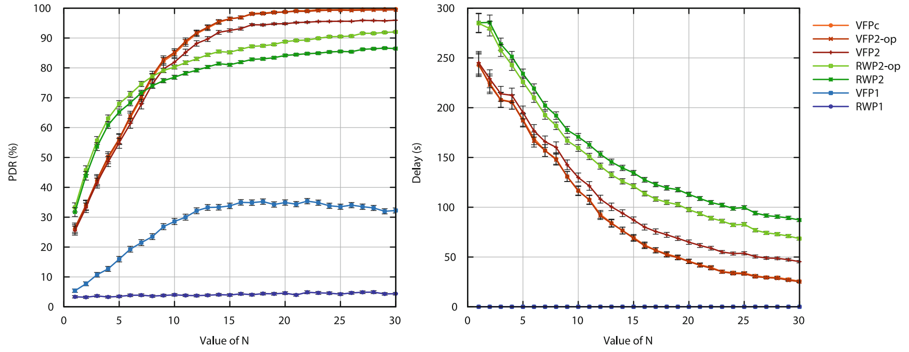

Fig. 5. PDR (left) and end-to-end delay (right) of the CBR packets received by destination node D, versus the number N of initial survey nodes.

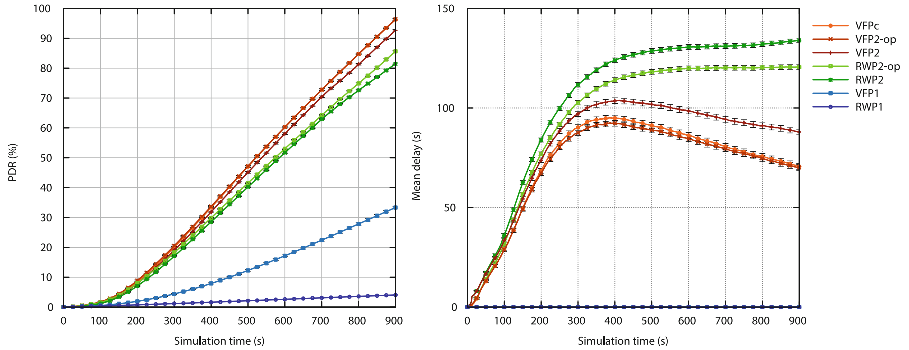

Fig. 6. PDR (left) and average end-to-end delay (right) of the CBR packets received by destination node D, versus simulation time. $N = 15$.

evaluate the other schemes. Figure 5 shows the PDR and end-to-end delay of the CBR transmissions between both traffic nodes for all considered schemes, with a varying initial number N of survey nodes in the network, such that $1 \leq N \leq 30$.

General performance outcomes. It can first be observed that both RWP1 and VFP1 exhibit low end-to-end delays (below 15 ms for all values of N) compared to the other schemes. However, VFP1, with a PDR reaching a maximum of around 35% for $16 \leq N \leq 18$, represents a significant improvement over RWP1 and its lower PDR, consistently below 5%. As we detailed in [15], the low performance of RWP1 can easily be explained by the low node density and the relatively high velocity of the survey nodes, in the range of [5, 10] m/s, which goes beyond the regular pedestrian-type speeds found in most MANET deployment scenarios. Likewise, the PDR results of VFP1 are understandably constrained by the unavoidable time needed for the mobile nodes to physically move and connect the traffic endpoints. We however verified in [15] that the performance of VFP1 is close to that of an ideal-theoretic mobility control scheme where node positions would always be known. Consequently, further design improvements of VFP1 based solely on packet-forwarding routing would offer limited perspectives, especially regarding PDR. In contrast with RWP1 and VFP1, the five epidemic-enabled strategies share a sharp improvement in terms of PDR, at the expense of significantly lengthened delays, as Fig. 5 illustrates. In any case, these schemes have an increasing PDR with N and, in this regard, will systematically outperform RWP1 and VFP1 for $N > 3$.

At this stage, a sharp distinction can also be made between the five epidemic-enabled schemes, on both the criteria of PDR and end-to-end delay:

- VFPc, VFP2 and VFP2-op systematically yield better PDR results than RWP2 and RWP2-op for $N \geq 9$: for instance, when $N = 15$, the former set outperforms the latter, in terms of PDR, by 7% to 15%. Figure 6 (left), which shows how PDR evolves with time for $N = 15$, confirms that the VFP-and-epidemic-based schemes consistently outmatch the RWP-and-epidemic-based strategies at all times. Further, while for $N = 30$, all PDRs are contained between 96% and 99.5%, VFPc, VFP2 and VFP2-op obviously converge faster and are already above 96% for $N \geq 15$. However, for $N \leq 7$, RWP2 and RWP2-op always outperform VFPc, VFP2 and VFP2-op regarding PDR. This is easily explained by the fact that low values for N do not allow the VFP-based controlled mobility protocol to successfully establish communication chains. Instead, the VFP-enabled strategies here forms incomplete chains which are not sufficiently long to create an end-to-end path between both user traffic endpoints, and which waste intermediate nodes which could otherwise explore the overall area and opportunistically transmit packets, hereby increasing PDR. Yet, for $N > 7$, using a VFP controlled mobility protocol starts making more sense than applying a simple RWP mobility scheme to the network nodes.
- With respect to delay, Fig. 5 (right) shows two general trends: first, VFPc, VFP2 and VFP2-op yield lower end-to-end delays for any value of N. In addition, as already observed for PDR, the optimized schemes (i.e. VFP2-op and RWP2-op) behave better than their counterpart with default values, which was expected by construction. Moreover, Fig. 6 (right) illustrates how the average end-to-end delays from CBR packets received since the start of the simulation evolves with time, for $N = 15$. VFPc, VFP2 and VFP2-op clearly exhibit a maximum at simulation time $t \approx 400$ s, which corresponds, for the considered scenario, to the statistical time at which the VFP-based communication chain is established, and packets can be transmitted along the multi-hop path formed by the relay nodes. Subsequent CBR packets are then likely to reach their destination endpoint with significantly lower delays, decreasing the average end-to-end delay accordingly. Instead, the average end-to-end delays of RWP2 and RWP2-op never decrease with time. At the end of the total simulation time, this delay reaches a steady point with RWP2-op while it still increases with RWP2.

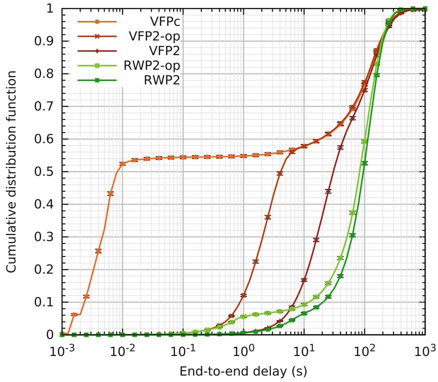

Fig. 7. Cumulative distribution function of the end-to-end delays.

Performance of VFPc. The specific case of the full-featured, dual routing stack, VFPc, is now singled out and analyzed. Although VFPc uses the epidemic stack with default parameter values, its PDR results are however almost identical to that of the optimized VFP2-op, as Fig. 5 (left) and Fig. 6 (left) illustrate. The same can be said in terms of mean delays, as shown by Fig. 5 (right). Figure 6 (right) shows that VFP2-op slightly outperforms VFPc during a part of the simulation, although the average delays of both schemes eventually match. As a result, both schemes exhibit a comparable performance in terms of PDR and mean delay, although VFPc has a more frugal behavior regarding overhead, thanks to the use of default epidemic parameter values which generates less control messages.

Furthermore, an in-depth study of the delay distributions reveals a solid argument, besides epidemic control message overhead mitigation, to consider the use of VFPc. Figure 7 displays the CDF of the end-to-end delays related to the CBR traffic for all epidemic schemes. The RWP-based schemes yield the longer delays: only 1% and 6% of the CBR packets are respectively received within 1 s when using the RWP2 and RWP2-op schemes. For the VFP-enabled schemes, the distributions significantly vary: while about 56% of CBR packets are received within 7 s when using VFPc or VFP2-op, only 8% of CBR packets are received in that time windows with VFP2. However, almost no packet is received within 100 ms for VFP2-op, versus more than 54% with VFPc. Even more significantly, a dual pattern can be observed from the CDF curve of VFPc: 52% of the user traffic is received synchronously, within 10 ms, through the VFP-enabled communication chains, while the rest is received asynchronously, with delays exceeding 1 s, via DTN-based opportunistic exchanges. This confirms the interest of enforcing controlled mobility principles: with VFPc, as much user traffic as possible is received with low delays when the VFP-based topology is fully formed, while the rest is conveyed via packet replication, with longer delays.

5 Conclusion

In this work, we presented VFPc, a distributed controlled mobility strategy relying on virtual forces, which enables a flock of network nodes to move cooperatively and form multi-hop communication links where needed. The use of VFPc is particularly justified in the context of disaster-relief communications and more generally, rapidly formed networks, which need to provide an efficient network coverage with a reduced set of network equipment. In that regard, we presented the architectural principles of VFPc and a dual routing framework that allows switching from packet-replication to packet forwarding (and reciprocally), based on whether a VFP communication chain is established or not. We then evaluated this strategy via a set of simulations which confirmed that the joint use of the VFP controlled mobility and a dual packet forwarding-replication routing stack yields the best performance in terms of packet delivery and delays, compared to other MANET- or DTN-based schemes. In addition, delay CDF results show that VFPc incurs two distinct communications phases during which the user traffic may be transmitted with very low delays, when VFPc communication chains are established, or with more elastic delays otherwise. An application aware of the times at which it enters synchronous or asynchronous modes may offer new perspectives in terms of user experience despite challenging network conditions. In the future, we plan to implement VFPc and its routing framework on a swarm of UAVs and further assess VFPc performance via experimentation.

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