Using UHF Connectivity to Off-load VHF Messaging in Tactical MANETs

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***Abstract*—Future mobile tactical networks are being developed to support an increased variety of data services (e.g. Blue Force Tracking, intelligence image or video reporting) in addition to the more traditional voice services. Such networks rely on an IP-based MANET stack, running over a UHF (Ultra-High Frequency) radio interface. Unlike legacy VHF (Very-High Frequency) radios, characterized by low bitrates but long-range coverage, the new UHF radios trade shorter transmission ranges for significantly higher bitrates. In particular UHF topology is subject to frequent splits and merges, resulting in intermittent UHF end-to-end connectivity. In this paper, we propose and evaluate a dual-radio broadcast message delivery mechanism. While the VHF radio guarantees eventual delivery, we show that exploiting intermittent UHF connectivity can greatly improve network performance. This is particularly true for delay-tolerant traffic.**

***Index Terms*—Delay tolerant networking, heterogeneous networking, epidemic routing**

I. Introduction

The next generation of MANET radio networks will support new forms of operational engagement, such as Network Centric Warfare [1]. Massive transformation programs are following this path in the US [2] or in France [3], and in this very active field products such FlexNet [4], [5], Falcon III/AN [6], or ESSOR [7], are either under development and starting to be deployed. Whereas legacy digital tactical radio networks focused on the needs to provide deployable means for long-range voice communications on the battlefield, the MANET radio networks also enable new higher bitrate data services such as blue force tracking (BFT), multi-media content delivery, remote control of sensors.

To meet this ambitious goal, the MANET radio networks rely on a mix of several radio air interfaces. New very-high frequency (VHF) waveforms retain long-range communication capabilities, and provide increased bit-rates dedicated to the new data services. These systems, and their evolutions or successors, will gradually be adopted by forces and coexist with the older legacy radio systems.

At shorter ranges, new ultra-high frequency (UHF) radios are being progressively deployed to military forces, starting at the platoon level before moving up. While these systems are more sensitive to adverse propagation conditions and suffer from frequent connectivity disruptions due to sparse deployment, node mobility, and short ranges, they do however offer significantly higher bitrates. They are therefore intended to support rich communications services among nodes in close geographic proximity (e.g., a platoon). For instance, the tactical situation might be enriched with multi-media observations shared among groups of nodes. Novel data-centric services are bandwidth intensive. Given the capacity limitations of VHF and the intrinsically local nature of many types of data, these new services may initially be offered only over UHF.

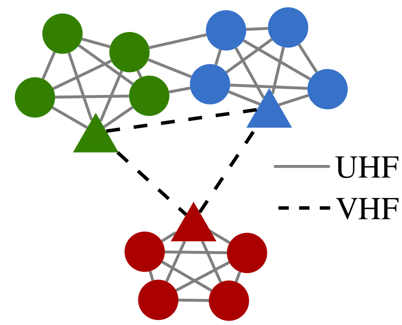


Fig. 1. Hybrid deployment of VHF/UHF radios. All nodes are equipped with UHF radios. Leaders, depicted by triangles, also have a VHF radio.

Extending these bandwidth-intensive services from the platoon to higher echelons is extremely challenging. Indeed, while specific equipment or operators may relay messages from the VHF to UHF networks and back, relaying such traffic will quickly saturate the VHF network's bandwidth. In this paper, we consider *hybrid* UHF/VHF networks in which all nodes carry a UHF radio while a few also carry a VHF radio (see Fig. 1). For example, since end-to-end UHF connectivity cannot be guaranteed at the company level, the VHF radio is an obvious candidate to relay company-wide messages between disconnected UHF networks. Due to their greater coverage, VHF ressources are precious. For the replication of delay-tolerant messages, we show that opportunistic inter-platoon UHF connectivity enables massive off-loading of traffic from the VHF network.

More specifically, we simulate company and platoon mobility using the Reference Point Group Mobility (RPGM) mobility model [8]. Using various waiting-based VHF relaying strategies, we show the following:

- enabling inter-platoon UHF communications significantly increases both the network's capacity and message delivery ratio in all cases;
- under light loads, as expected, offloading traffic from the VHF radio incurs longer delays;

- under heavier loads however, this trade-off disappears and strategies that wait as much as possible before using the VHF radio do not compromise on either delivery ratio or delay while massively off-loading traffic from the VHF network.

The remainder of the paper is structured as follows. Section II proposes a review of the relevant related work. We then model an hybrid tactical MANET in Section III. Under our assumptions on tactical networking and mobility, we highlight the network connectivity dynamics within an UHF network. Taking advantage of those connectivity opportunities, we propose a protocol to off-load network traffic from the VHF network to the UHF network in Section IV. We then evaluate different off-loading strategies using simulations and we discuss the main results in Section V.

II. Related work

The techniques developped in the paper are inspired by work on Disruption-Tolerant Networking (DTN) [9]. Messages are exchanged using a store-and-forward paradigm. In a reversal of traditional MANET routing, node mobility is no longer a problem to be handled but an advantage that can be used to greatly increase a network's capacity at the cost of longer delivery delays [10].

Traditional DTN work has focused on unicast routing issues. Early work relied on scheduled contacts for routing DTN messages [11], [12], [13]. For the more general case of opportunistic (or random) contacts, one can distinguish two main families of solutions. The first one relies on on some utility function to help nodes decide which next relay node to choose for a given destination. The utility functions capture some knowledge of the node's context. One can use past frequencies of contacts [14], or introduce adaptive dropping policies [15], Kalman filtering [16] or minimise expected delay [17]. The second one applies *epidemic* routing, which consists in flooding the message across the network [18], [19]. The key issue is thus to control the flooding process. One can limit the number of copies [20], or hop limits or timeouts [21]. All these approaches distribute multiple copies of packets, they ensure higher reliability of delivery, and lower latency, but they imply high buffer occupancy and high bandwidth consumption.

The offloading technique described in the paper takes advantage of all the transfer opportunities created by mobility to disseminate data. However, DTN protocols do not aim at benefiting from coexisting radio technologies that spatially overlap and that fulfill complemenbtary communication needs. Furthermore, unlike traditional DTN approaches, our offloading techniques are tailored to broadcast data, not unicast. Most importantly, our hybrid VHF/UHF solution can guarantee delivery within a certain maximum delay *as long as the VHF is not saturated*. In this last respect, it shares some features with the hybrid cellular/WiFi networks of the Push-and-Track framework [22].

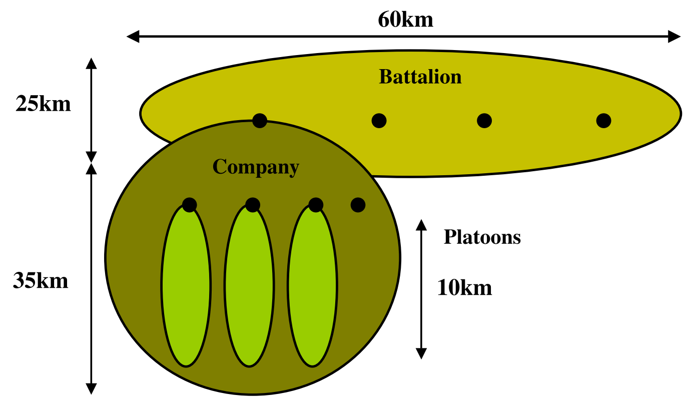


Fig. 2. A simplistic view of military deployments.

III. Modeling Hybrid Tactical MANETs

A. UHF and VHF radios

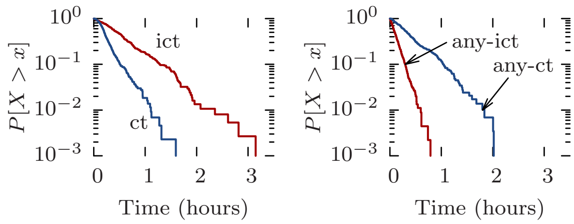
Tactical radios rely on time-slotted architectures for multiplexing data and voice communications. Therefore the full bitrate of these radios is not available for lower-priority services [23]. We assume that the VHF data channel is divided into two logical channels: a data channel with an effective throughput of 4 Kbit/s; and a control channel with an effective throughput of 100 bit/s. The latter is to ensure that acknowledgments are received in a timely manner and do not suffer from congestion on the data channel. Ad-hoc VHF connectivity between leaders of each platoon is assumed to exist at all times.

As wireless propagation models are not the focus of this paper, UHF connectivity uses a simple disc-based model in which two vehicles can communicate if they are within 5 km of each other. Altogether, the company mobility and connectivity models ensure that the UHF topology of each platoon is fully connected. The UHF shared effective throughput is set to 512 Kbit/s.

We assume that all network data traffic is progressively disseminated using store-and-forward radio transmissions over both the VHF and UHF radios. Typically, the underlying waveform (UHF or VHF) provides hop-by-hop flow control and reliability. We therefore consider that the reliability service over the lossy links is taken care by the waveform. While tactical radios may provide reliable point-to-multipoint communications [24], we do not assume these are available in this paper. If available though, they would sigificantly improve performance on both the UHF radio by reducing competition between inter and intra group transmissions, and on the VHF radio by lowering the number of transmissions per message (See Section IV).

B. Company mobility

Tactical mobility during a field deployment is strongly structured by military doctrine. As a result, tactical networks are usually well organized. Typical battalions (e.g., 200 vehicles) [23] are generally hierarchically subdivided into companies (e.g., 50 vehicles) and platoons (e.g., 10 vehicles).



(a) Contacts (ct) and inter-contacts (ict)

(b) Any-Contacts (any-ct) and inter-any-contacts (any-ict)

Fig. 3. Complementary CDFs group contact distributions based on UHF connectivity.

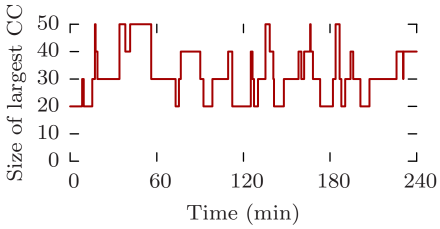


Fig. 4. Size of largest UHF connected component for one run of the simulated mobility

In space, as shown in Figure 2, these hierarchically organized units schematically evolve in concentric areas of 60km x 60km for battalions, 35km x 35km for companies, and 10km x 10km for platoons.

The results of this paper are therefore based on the simulated mobility of a company using the Reference Point Group Mobility (RPGM) model [8]. This model is well suited to the highly structured military mobility and easily extensible for more specific situations such as disaster area recovery, urban warfare, reconnaissance, and special operations [25]. Indeed, all mobile nodes are divided into groups which have a logical center. Group nodes move randomly relatively to the group center and always remain with a maximum distance of it. The movement of the logical centers can be defined independently.

Our simulated company moves in a 30km x 30km area. It is divided into 5 platoons (or groups) of 10 vehicles. While feasible, we purposefully don't assume a specific operational procedure for generating our mobility. Consequently, the speed and check points of each platoon's logical center are obtained using the Random Waypoint mobility model. Within each platoon, we enforce a maximum distance (or group radius), set to 2.5km, between the platoon leader and its members.

When offloading traffic from the VHF radio, the most important parameter is the UHF connectivity between groups. Fig. 3 illustrates the dynamics of the inter-group connectivity. We consider two groups to be in contact if any two nodes of either group are with UHF range of each other. The median contact and inter-contact durations are respectively 12 and 27 minutes. We define the inter-any-contact duration as the time during which a group in not in contact with any other group. Conversely the any-contact duration is the time during which a group is in contact with at least one other group. The median inter-any-contact and any-contact durations are respectively 6 and 19 minutes. Fig. 3b shows the complementary cumulative distribution functions for contact and inter-any-contact durations. Fig. 4 shows the variation of the size of the largest UHF connected components over time for one run of the simulated mobility. At any given time, there are at least 2 or 3 connected groups. On some rare occasions however, the UHF network is fully connected.

IV. Off-Loading in Hybrid Tactical MANETs

A. Protocol overview

We propose to off-load traffic from the VHF radio network at the company level. The traffic that the protocol supports is broadcast-based, and provides an efficient forwarding service across platoons. In the company, each platoon is composed of two types of radio nodes: *Regular* and *Leader*.

Regular nodes are equipped with a UHF radio. They propagate messages epidemically [18]. When two regular nodes are in UHF range of each other, they discover each other and exchange a list of the messages currently held in their buffers if they share the same UHF network. Based on this information they then exchange the messages that either is missing to ensure that both hold the same messages. Messages that are closer to their expiration time are sent first.

Leader nodes are equipped with both UHF and VHF radios. Typically, each platoon has a single leader node. They are responsible for making the decision of when (if ever) to relay a message to the other platoons using the VHF radio. While *Leaders* disseminate messages epidemically on the UHF radio, they also bridge the UHF and VHF networks in the following way upon receiving a message M:

- M was received on the UHF interface:
  - M originated from my platoon: take responsibility for disseminating M to the other platoons. After taking responsibility for M, the decision of when to relay it using the VHF radio is based on the strategies outlined in the next section. A leader node will never transmit a message that did not originate in its platoon over the VHF radio.
  - otherwise, send an acknowledgement to the platoon leader of M's sender. Since platoons maintain high-speed UHF connectivity, an acknowledgement from its leader means that all platoon members have received (or will soon receive) the message.
- M was received on the VHF interface: send an acknowledgement to the platoon leader of M's sender, add M to my local message buffer, and try to disseminate it epidemically within my platoon.

B. Inter-platoon forwarding strategies

In order to evaluate the effectiveness of VHF radio offloading, we define the following strategies for inter-platoon routing using the mixed UHF-VHF connectivity:

Local-only UHF: each platoon operates a separate UHF network. Communication between platoons is only possible

TABLE I
SIMULATION PARAMETERS

Parameter	Value
Simulation area	30km x 30km
Simulation duration	4 hours
Groups	5 platoons of 10 vehicles
Group radius	2.5 km
Group center speed	4 to 20 m/s
UHF range	5 km
VHF range	30 km
UHF link throughput	512 Kbit/s
VHF link throughput	4 Kbit/s
Message size	10 KBytes
Acknowledge size	10 Bytes
Buffer size	100 MBytes

using the VHF radio. This strategy constitutes the worst-case scenario as no VHF offloading is possible.

All of the following strategies use a *global* UHF radio where UHF communications are possible between any two nodes in range of each other even if the belong to different platoons.

Immediate: Relay messages over the VHF radio as soon as possible. Leader nodes schedule transfers to all other leaders. If a leader receives a message on its UHF interface while it is receiving it on its VHF interface, it aborts the ongoing VHF transfer.

Early: Wait a little before relaying over the VHF interface. More formally, let t_e be a message's expiration time, t_c its creation time, and t the current time. Let $\alpha = 3/4$. If $t_e - t < \alpha(t_e - t_c)$, then relay the message.

Midtime: As above but with $\alpha = 1/2$.

Late: As above but with $\alpha = 1/4$.

Last moment: Given the message's size and the VHF radio's bitrate, estimate the time D it would take to schedule VHF transfers to all the other leaders. If $t_e - t < 2D$, then relay the message.

In all cases, if a leader can choose from several messages to send using the VHF radio, the one with the nearest expiration date will be sent first.

V. Results and Analysis

A. Simulation setup

Every few seconds, during 4 hours, a new 10 Kbyte message is created by a random node with a certain lifetime. For example, this could correspond to a low-resolution image with some text. The results in the section are all based on two variable parameters: the *message creation rate* and the *message lifetime* (i.e., the time before the message expires). All simulation parameters are summarized in Table I.

For the purposes of this paper, we built our own simulator, heavily inspired by the ONE DTN simulator [26]. In particular, it retains the contact-based ad hoc communication model from ONE, with its simple interference model in which a node may only communicate with a single neighbor at the same time. Unlike ONE, it accommodates several message classes (e.g. data or control) and unicast routing can coexist with broadcasting.

The results in this section consider three values of the message lifetime: 5 minutes (e.g. fairly urgent), 20 minutes, and 1 hour (e.g. low priority). The following metrics were measured.

VHF load: The sum of all bytes transferred on the VHF data and control channels divided by the measurement period. When the average VHF load reaches 4Kbit/s, the VHF channel is saturated.

Delivery ratio: The average fraction of nodes that receive a message before it expires. In practice, even in the worst case, each node receives all messages that originated in its platoon. With 5 groups of 10 nodes, this means that the delivery ratio doesn't fall below 0.2.

Maximum delivery delay: The average delay experienced by the last node to receive a message. This metric only takes delivered messages into account. Therefore messages that were never delivered beyond their original platoon will have a very low maximum delivery delay.

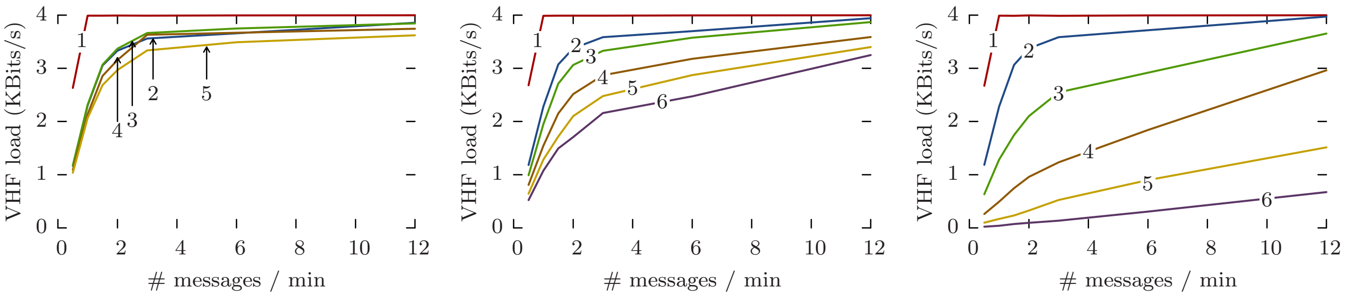
A simulation run consists of a mobility generation followed by a message routing simulation. For each message delay, message creation rate, and relaying strategy triplet, these metrics are computed on the "steady" period between the 1st and 3rd hours and averaged over 10 runs. 95% confidence intervals were calculated but are tight and do not overlap (except for the global UHF strategies in Figs. 5a and 6) and were omitted for clarity.

B. Inter-group UHF connectivity significantly increases bandwidth

Given our simulation parameters, transmitting a message using the VHF radio takes about 20 seconds. In our scenario, if no inter-group UHF connectivity exists then each message will use the VHF radio for 80 seconds (1 transmission to each of the other 4 leaders). Fig. 5 plots the average VHF load against the message creation rate for different message lifetimes. When more than one message is created per minute, the VHF radio is completely saturated and its average delivery ratio plummets (Fig. 6). However, as soon as inter-group UHF connectivity is allowed, that extra bandwidth prevents the saturation the VHF radio and makes delivery ratio degrade at a much slower rate when increasing the message creation rate.

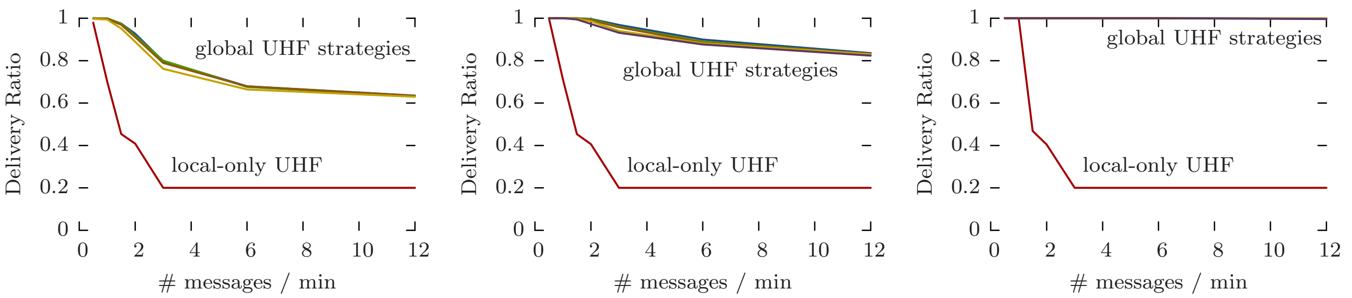
C. Delivery ratio is insensitive to waiting

Fig. 6 plots the average delivery ratio against the message creation rate. For all message lifetimes, the delivery ratios for the *immediate*, *early*, *midtime*, *late*, and *last moment* are nearly identical (i.e., their 95% confidence intervals overlap). This is a surprising result. As expected, the decision of when to transmit over the VHF impacts both the maximum delivery delay (e.g. messages transmitter earlier are more likely to



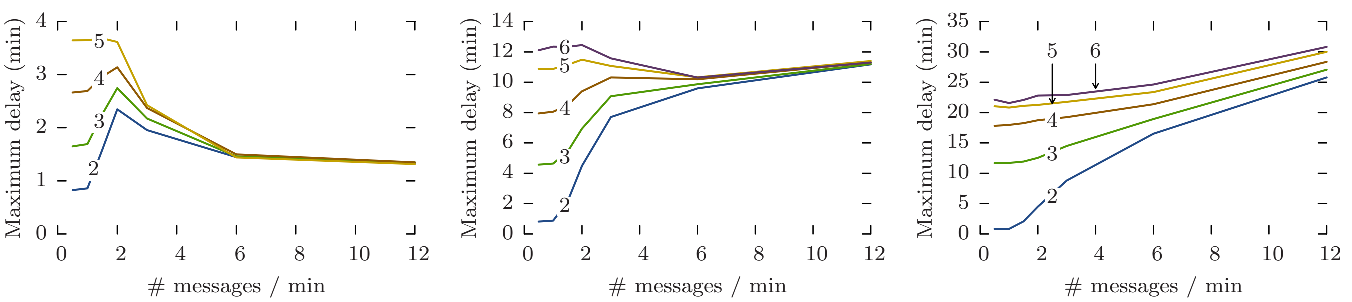
(a) 5 min (b) 20 min (c) 1 hour

Fig. 5. Average VHF load vs message creation rate for different message lifetimes. (1) local-only UHF, (2) Immediate, (3) Early, (4) Midtime, (5) Late, (6) Last moment



(a) 5 min (b) 20 min (c) 1 hour

Fig. 6. Average delivery ratio vs message creation rate for different message lifetimes. Global UHF strategies refer to the Immediate, Early, Midtime, Late, and Last moment strategies.



(a) 5 min (b) 20 min (c) 1 hour

Fig. 7. Average maximum delivery delay vs message creation rate for different message lifetimes. (1) local-only UHF, (2) Immediate, (3) Early, (4) Midtime, (5) Late, (6) Last moment

reach everyone earlier, see Fig. 7) and VHF load (e.g. earlier VHF transmissions may turn out to have been useless if the two group later come within UHF range of each other, see Fig. 6). However, particularly for the *Late* and *Last Moment*, one would expect the spared VHF bandwidth to be used to send extra copies and increase average delivery ratio.

This is not the case for the following reason. The UHF topology oscillates between fully connected phases, where VHF transmissions can be unnecessary and delivery ratio is 1, and split phases, when the VHF radio may be continuously used at 4Kbit/s but fail to deliver all messages in time.[1] During the fully connected phases, the waiting time is mostly irrelevant. During the split phases, since message are prioritized according to their expiration date, if messages are created faster than the time it takes to send one over the VHF radio (20 s, i.e. 3 messages per minute), then the VHF radio will rarely schedule more than 1 transmission per message. For example, the *Immediate* strategy will send its one copy earlier than the *Late* strategy but both will on average only send one copy.

[1]This also explains why the average delivery ratio can be less than 1 even though the average VHF load is less than 4Kbit/s

D. Delivery delay is insensitive to waiting for high message creation rates

Fig. 7 plots the average maximum delivery delay against the message creation rate. These plots have a complicated profile due to several competing influences. Keep in mind that this metric only accounts for delivered messages, therefore a message that was never disseminated outside its local platoon may have a low maximum delivery delay.

With a 5-minute message lifetime (Fig. 7a), and a low message creation rate (e.g. 1 message per minute), the *Immediate* strategy clearly achieves faster deliveries. As the message creation rate increases, so does the competition for the VHF bandwidth. As expected, the maximum delivery delay initially increases. However it quickly decreases for all strategies when more than 2 messages are created every minute. This is an consequence of the decreasing delivery ratio (Fig. 6a. Fewer messages are reaching all members of the battalion, but the maximum delivery delay of the successful transmissions are lower. Conversely, when the delivery ratio remains at 1 (e.g., when the message lifetime is 1 hour in Figs. 6c and 7c) the maximum delivery delay increases monotonously.

Furthermore, regardless of the message lifetime, the maximum delivery delay for all strategies eventually converge. This happens when the message creation rate is greater than 6, 12, and 30 for, respectively, 5-minute, 12-minute, and 1-hour message lifetimes. *Beyond this convergence point the VHF radio's contribution is negligible compared to the UHF radio*. The shorter the message lifetime the lower the message creation rate that achieves this convergence point.

E. Waiting enables massive VHF radio offloading

We have seen that choosing to delay relaying over the VHF radio involves no tradeoff on delivery ratio. Furthermore, the tradeoff on maximum delivery delay decreases with the message creation rate. When message lifetimes are short (e.g. 5 minutes), node mobility is not sufficient to offload significant amounts of traffic from the VHF radio using epidemic UHF-dissemination (see Fig. 5a). However, for longer message lifetimes (e.g. 1 hour), the offloading is very significant. For example, when creating 6 new messages per minute with a 1 hour lifetime, the *Last Moment* strategy offloads 90% more traffic than the *Immediate* strategy. When the message lifetime is long and the traffic exceeds the capacity of the VHF radio, the *Last Moment* strategy really shines, by massively offloading traffic from the VHF without compromising on either delivery ratio or delivery delay.

VI. Conclusion

In the context of next-generation hybrid UHF/VHF radios we have proposed a broadcast protocol that vastly improves performance (delivery ratio and delay) over using either VHF or UHF alone. As the delay tolerance increases, significantly more VHF traffic can be offloaded to the UHF radio, thereby freeing precious ressources for other company-wide communications.

While only broadcast performance is studied in this paper, our dual-radio approach can be extended to support unicast, anycast, or multicast traffic as well. For reliable delivery, we considered store-and-forward transmissions while the underlying waveforms may provide reliable point-to-multipoint mechanisms (at least for short messages). A joint design with existing waveforms could yield an even better performance of our protocol. Furthermore, while the RPGM mobility model can cover a wide variety of situations, empirical mobility from tactical exercises could provide further insights into our offloading strategies.

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