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Carreau: CARrier REsource Access for mUle, DTN applied to hybrid WSN / satellite system

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Abstract—Both WSNs (Wireless Sensor Networks) and observation satellites are able to get measurements from a geographic area. To interconnect these technologies, we propose to use a store-carry-and-forward architecture relying on the DTN (Disruption and Delay Tolerant Networking) Bundle Protocol. This architecture aims at being generic, so it is application-agnostic and suits a wide range of scenarios. WSN may collect sporadically large data volume while terrestrial stations communicating with Low Earth Orbit (LEO) satellites have to endure long link disruptions when the satellite is not in the line of sight. These sporadic growths within the WSN coupled with the large latency on satellite links require to schedule data to provide quality of service to several flows. We propose a scheduling policy based on deadline of Bundles and compare it with classical DTN solutions.

Index Terms—Low Earth Orbit satellites, Disruption Tolerant Networking, Scheduling

I. INTRODUCTION

Wireless sensor networks and observation satellites are used to monitor systems either locally or remotely in a wide spectrum of domains; such as weather forecast, greenhouse gases monitoring or military applications [1]–[3].

Satellites can sense data within wide areas [4]. Data sensed from an aircraft or a spacecraft is different and complementary to data collected on the field. Depending on the sensing environment, a satellite would collect data better than other technologies unadapted to the conditions. For example, in underwater sensor networks in the sea, a satellite can collect data from surface buoys [5] while it is not feasible to install wires for each network.

Remote sensing is a very challenging topic for satellite applications [6], [7]. For example, air quality forecasting can be improved thanks to observations from satellites [8]. Both satellites and WSN allow to collect information from a sensing field. Combining data from these technologies allow to get more accurate information without adding other communication technologies. Data from in-situ sensors would be gathered within a satellite terminal relaying data to the satellite when it is in the line of sight.

Observation satellites mainly use Low Earth Orbits (LEO). Such satellites suffer from disruption between the terrestrial stations and the satellites. WSN can also suffer from disruptions. It is compulsory to use protocols able to handle these link disruptions. Hence satellites would transmit their own sensed data and data gathered from the WSNs.

An application-agnostic architecture able to combine data sensed from in-situ sensors with satellite one was proposed in [9]. This architecture relies on the Bundle Protocol as overlay. Such an architecture is relevant because several technologies may communicate while the topology or constraints are not the same within distinct parts of the network.

When monitoring systems, a crisis can occur. Furthermore, during a crisis, the connectivity of the network may not last long. Critical data have to be forwarded as fast as possible to guarantee that information is still accurate when it is received. The long periods of link disruptions are a drawback for delivery of short lifetime data. Then we focus on how to maximise at low cost delivery within such a network.

We first analyse the studies realised in DTN domain, then present our contributions and finally discuss about the latter.

II. RELATED WORK

DTN architectures and protocols, which were initially developed for an interplanetary scenario, present useful mechanisms for this hybridisation study. The WSN as well as the satellite links in a LEO context suffer from disruptions.

The main challenge for DTN is to achieve high packet delivery ratio with an average delay as low as possible. Several mechanisms, protocols and algorithms have been proposed to enforce such a property. The authors in [10] provide a classification, allowing to compare the different classes of DTN routing protocols. Protocols such as MaxProp [11] or Epidemic [12] rely on replicating the messages to increase the probability of delivery. The former uses the delivery likelihood through a path to replicate messages while the latter uses summary vectors of Bundles seen by nodes to determine whether a Bundle shall be replicated. The Spray And Wait [13] protocol replicates a fixed number of copies of Bundles during the Spray phase and delivers directly these copies at destination during the Wait phase. A second version of the PROPHET protocol providing better performance than the previous version has been recently proposed in [14].

In DTN context, the existence of a path between source and destination is very unlikely, and standard routing protocols fail at computing a route [15]. Most of DTN routing protocols focus on replication to achieve high packet delivery ratio. However, the main drawback for flooding-based protocols is the excessive use of resource. Within a sparse WSN context,

these protocols consume too much energy. In a data mule or satellite context, resource is wasted by such solutions. It is necessary to look for other methods of improvement.

Another challenge in DTN is scheduling and queueing policies. When congestion occurs the selection of the best-to-drop Bundles has been shown to increase delivery ratio. A buffer management policy has been proposed in [16] to maximise the average delivery ratio. Buffer replacement and scheduling schemes have been proposed in [17] to improve the performance of the network thanks to the knowledge of inter-meeting and contact durations. These schemes are based on the replication number and speed of dissemination of messages. This information about the messages is kept by each node and exchanged between them at each encounter. In [18] a resource allocation algorithm is proposed. This algorithm does not rely on the future state of the network. Their distributed algorithm requires from each node to know all other nodes possessing the messages they carry. Hence, at each encounter, nodes exchange their message data. The authors of [19] propose an algorithm, the Storage Policy, improving the performance of a network by deriving the maximum benefit provided by storage. The storage shall be considered in conjunction with routing to allow this calculation. These results are useful in a DTN context, since it is possible to maximise the delivery ratio without using unnecessary storage capacity.

Nevertheless, these schemes may not provide good performance for a satellite with a data mule scenario. We propose to analyse an architecture inspired from [9]. Several WSNs are deployed with a satellite terminal within each one. A LEO satellite collects data from these sensing fields.

The problem consists of a set of terrestrial gateways relaying data to a LEO satellite. The link between the satellite and stations is most of the time unavailable. We consider two traffic classes. These flows are identified by their fickle nature. The lifetime of Bundle Protocol Data Units (Bundles) is linked to this nature. Hence, the more fickle data is and the less long its carrying message lasts. Stations do not have the possibility to know the data volume other stations have to relay to the satellite. We study the results in terms of performance on the system when a growth on the critical traffic occurs.

III. INVESTIGATED STUDY

A. Study scenario

A study scenario of prevention and monitoring of wildfires through WSN and observation satellites suits the proposed model. The motivation for this study comes from the French space agency aim to develop multi-use solutions to gather observation while reducing the cost of satellite missions. The use of common spacecrafts for several programs illustrate this willingness. For instance, the PROTEUS System as well as the MYRIADE series are respectively platforms for mini- and micro-satellites. These systems use the same platforms and the same ground segment. New observation missions only have to focus on the payload instruments.

Two traffic classes are considered even if the proposed mechanism is adaptable to several classes. The first one has

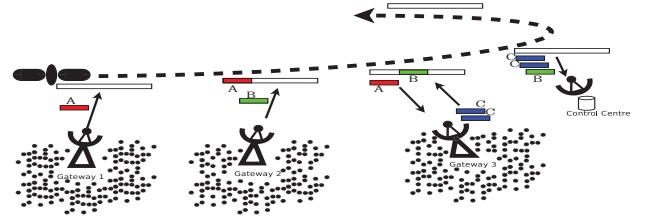


Figure 1. Carreau: an example

no strong constraints on delay delivery and the second one has a short expiry. The choice of representative metrics depends on the needs of the application. If data reliability is important, then the packet delivery ratio is the metric to maximise, if a transmission is very expensive, the number of retransmissions has to be minimised, and finally the application may require delay constraints. If we do not use replication-based transmissions, a lot of Bundles will be dropped each time the memory of the satellite is full. Furthermore gateways could suffer from starvation. In order to achieve a better delivery ratio at low resource cost, we propose to implement inside the routers a scheduling policy based on the expiry date rather than on the date of reception. This strategy is named Carreau, because like a special feat of a well-known game, Bundles are able to move another one and steal the place of the moved one. The algorithm 1 implements the scheduling strategy.

Algorithm 1 Scheduling policy within a satellite

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if  $bufferFreeSpace \geq threshold$  then
  if  $incomingBdle \in priorityFlow$  then
    store Bundle
  else if  $incomingBdleDeadline > bufDeadline$  then
     $bufDeadline \leftarrow incomingBdleDeadline$ 
    store Bundle according to deadline
  else
    store Bundle according to deadline
  end if
else
  forward to gw Bundles with largest deadline
end if

```

Figure 1 represents how Carreau works for a round of a satellite with one flow. Bundles B and C have shorter lifetimes than A. Hence, A is forwarded to the third gateway with the hope another satellite round will handle this Bundle before it expires. When we consider two traffic flows, the top-priority traffic is directly delivered to its destination.

This proposition can be compared to load balancing among several processors within a set of clusters [20]. Our proposition intends to balance the traffic while maintaining the priority and keeping the Bundles ordered relatively to their expiry date.

This algorithm guarantees top-priority data to be delivered as soon as possible and intends to deliver the maximum of low priority data. The capacity to delay the delivery of second class data should increase the delivery ratio since less packets would be dropped. Most DTN routing protocols focus on enhancing the overall delivery probability by replicating the Bundles. Since the traffic might suddenly grow, we cannot guarantee that each gateway is able to forward its data to a

satellite. Hence gateways might miss scheduled contacts and fail transmissions because of sudden traffic growth.

Our proposal achieves high Bundle delivery ratio with a delivery probability fairly distributed among the nodes without increasing the network load with replicas. The occurrence of starvation is avoided for a gateway whose available satellites are congested by fresher data than the gateway one.

The requirements of applications of our solution is that at least one data mule (such as the satellite) collects data from each station and forwards it to the destinations. We analyse the performance of our scheduling policy in a data mule context.

B. Problem Modelling

The mule is getting data from each station. We consider several traffic classes. These traffics are supposed to be periodic. We use this set of notations:

- S is the number of Bundles the mule can carry.
- N is the number of stations.
- $\lambda_{i,j}$ is the inter-arrival rate of traffic class i at station j .
- θ_i is the lifetime of any Bundle of traffic class i .
- D is the mule cycle time.
- C is the total number of mule cycles during crisis.

Let's assume that the more a traffic is priority, the shorter the lifetime of its Bundles is. Moreover each traffic class considered alone does not overload the system. The least priority traffic is always present in the network. Other classes correspond to several levels of criticality. Traffics are assumed to be fairly distributed among stations.

We use two steps for loss study. In a first time, we analyse the mean loss per mule round in the worst case, when all stations have Bundles from each class, for three forwarding policies:

- Full Transmission (FT), each station sends all data. The volume of Bundles exceeding mule capacity is lost.
- Full Upload (FU), each station sends data until filling the mule. Losses occur by expiry of non-carried Bundles.
- Carreau, Bundles with higher priorities are carried first. Less priority Bundles are "parked" on stations. Losses occur by lifetime expiry of "parked" Bundles.

In a second time, we study losses after crisis until there is no more loss.

1) Loss during crisis:

a) *Full Transmission*: FT is the most simple of the considered policies. The mean number of dropped Bundles n_{FT} is the number of exceeding Bundles on a mule cycle.

$$n_{FT} = \max \left(0, \left(\sum_i \sum_{j=1}^N (\lambda_{i,j} \times D) - S \right) \right)$$

It is obvious that FT provides an upper bound of lost Bundles. Indeed, all Bundles attempting to join the mule while it is full are dropped. Once crisis is over, there is no more loss.

b) *Full Upload*: Each station sends data ordered by priority and deadline until the mule is full. Then, there is a station index j_f such that after the mule has collected

data from this station, it can no longer accept incoming data. Bundles on stations whose position is greater than j_f will be removed from the network by lifetime expiry. Bundles with shortest lifetimes will be removed from the system earlier. The number of new Bundles pertaining to class i remaining on a station j after a mule round r is noted $n_{i,j}(r)$. Then priority Bundles will be removed first. We can calculate the mean number of dropped Bundles per mule round:

$$n_{FU} = \frac{\sum_i \sum_{j=j_f}^N \sum_{r=1}^C \left[n_{i,j}(r) \times \min \left(1, \sum_{l=r}^C \left\lfloor \frac{\theta_i}{l \cdot D} \right\rfloor \right) \right]}{C}$$

c) *Carreau*: Finally, we consider that within the network, the traffic is scheduled so that Bundles with higher priorities are transmitted first. Then if the mule is not full, Bundles with shortest remaining time-to-live are transmitted. Nevertheless, since the network is composed of stations which are not able to share information related to Bundles lifetimes, each station sends all Bundles to the mule and the mule keeps Bundles according to Carreau scheduling. Bundles with lowest priorities and greatest lifetimes are sent back to the next stations. At each cycle r , $n_{park_i}(r)$ Bundles are "parked". Indeed, they are "parked" for the next mule rounds until either deadline expiry or memory availability on satellite.

The mean number of lost Bundles per mule cycle n_{car} depends on the number of expiring Bundles at each mule cycle.

$$n_{car} = \frac{\sum_i \sum_j \sum_{r=1}^C \left[n_{park_i}(r) \times \min \left(1, \sum_{l=r}^C \left\lfloor \frac{\theta_i}{l \cdot D} \right\rfloor \right) \right]}{C}$$

2) *Loss after crisis*: Now, we analyse loss after crisis for Carreau and FU.

a) *Full Upload*: With FU, Bundles may be removed until there is no more stuck Bundles. Then for FU, at each cycle, the first stuck stations send at most $(S - j_f \times \lambda_1 \times D)$ stuck and incoming Bundles. Depending on whether it remains Bundles on j_f or not, j_f is incremented or not. If j_f is incremented, we apply again this algorithm until j_f is not incremented. When $j_f = N$, Bundles will not be removed anymore.

b) *Carreau*: Concerning Carreau losses may still occur while it remains Bundles from other classes than the least priority. At each cycle oldest Bundles from the most priority class are served and so on until there is no more Bundles from this class or the mule is full. If the mule is not full we apply the same process on less priority Bundles. At each cycle, expiring Bundles are removed from the system. After the number of cycles necessary to serve the remaining stuck traffic from crisis, no more Bundles will be lost.

We consider a simple situation with two traffics. Normal traffic Bundles can last more than one cycle and less than three. Critical traffic Bundles last at most one mule cycle. Their period of activity is the duration of a crisis.

Figure 2 represents the mean number of lost Bundles per mule round under the three policies detailed earlier. Losses are presented as a function of the existence period of critical traffic. We consider normal traffic takes 90% of mule capacity and critical data 60%.

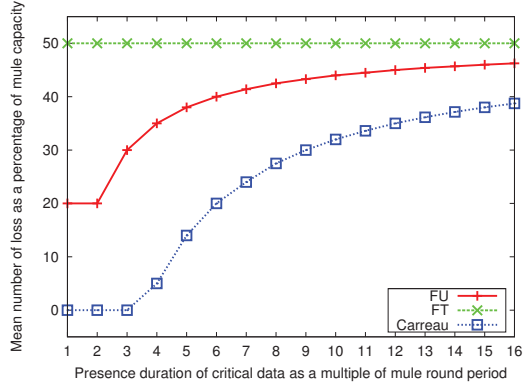


Figure 2. Loss as a function of critical data presence

Table I
SUMMARISED SIMULATIONS PARAMETERS

Number of satellites	5
Number of gateways	5
Simulation Duration	5 days
Bundles size	1MB
Inter-arrival intervals	[600, 900, 3600]

The results of Figure 2 indicate that FT policy is the worst. FU provides a better mean loss, but losses occur even at the first round by critical Bundles expiry. Carreau provides better results than others because Carreau transmits first high priority Bundles whose lifetime is shorter than others. Then critical data affects the performance for longer crisis. We have compared our proposal analytically to simple mechanisms in a peculiar scenario. To complete this study, simulations are run to better suit reality. For the remaining of this paper, we will compare Carreau to well-known DTN solutions.

IV. SIMULATIONS

A. Simulated Environment

In order to validate our proposal, we simulate the behaviour of the network thanks to "The One" simulator [21]. This simulator is adapted to test and validate routing and scheduling algorithms and more specifically in a DTN environment.

We consider five terrestrial stations which have to relay the Bundles incoming from a WSN. The volume collected by each terrestrial station is 1 MegaByte. This corresponds to the volume generated by ten thousands MicaZ motes transmitting 100 Bytes Bundles. All terrestrial stations create normal class Bundles. However, some of these stations can send during a certain period of time top-priority data. This shall model the stochastic nature of a wildfire start. Five satellite nodes have been implemented. To model their movement, we have analysed the orbits of five operational LEO observation satellites: Spot 4 and 5, Pleiades 1, SAC-D and EO-1.

As for the analytical evaluation, two traffic classes have been implemented. One is critical and has an inter-arrival period of

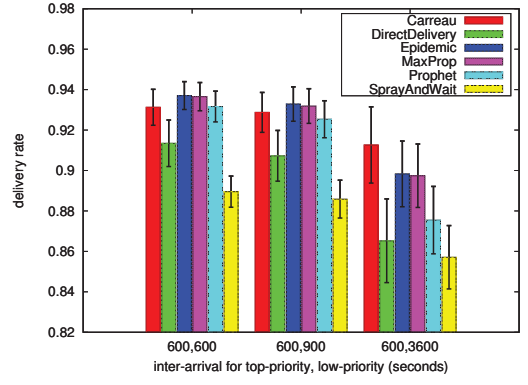


Figure 3. Overall Delivery Ratio

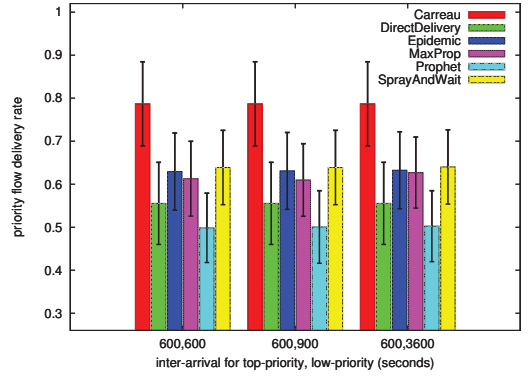


Figure 4. Priority-flow Delivery Ratio

600 seconds. For each simulation, the network goes from a critical phase to a normal state. The durations of these phases are randomly picked since neither crisis start nor duration are deterministic. In the critical phase both classes exist while in the normal stage, only standard traffic exists. We analyse the overall and top-priority delivery ratio and the overhead ratio with different routing algorithms and several traffic loads generated by modifying the frequency of data creation. Table I summarises the parameters for the simulations.

B. Results Interpretation

As shown on Figure 3, our proposition achieves, in main cases, the same performance as other typical DTN solutions with the overall Bundle delivery ratio. All solutions provide delivery ratio within the same range. Our proposal, Carreau, outperforms standard DTN protocols in the scenario with a large period for non-prioritary observations. This scenario is the one fitting best the reality. Measurements of critical data have to be more frequent when a fire starts.

Concerning the delivery ratio of the priority flow, our scheme is mostly better than typical DTN solutions such as Spray And Wait, Epidemic, MaxProp or Prophet. The proposed scheme provides also better performance than the Direct Delivery routing solution. The results provided by Figure 4 allow to observe that, with all scenarios, our proposition achieves better delivery ratio than the other protocols by at

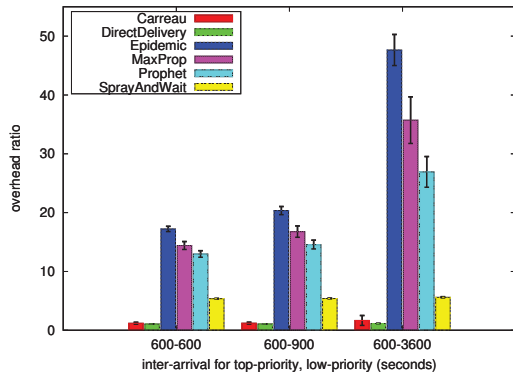


Figure 5. Overhead Ratio

least 15%. For less critical situations, the proposed scheduling achieves still better performance than other reference schemes.

These results show that while we get better performance on one flow, we do not disadvantage the global delivery ratio since we keep an overall Bundle delivery ratio in the same range than the ones provided by well-known DTN routing protocols.

Furthermore, thanks to Figure 5, we observe that our proposition provides significant performance enhancement at lower cost than other protocols, as far as overhead is concerned. Indeed, apart from the Direct Delivery solution which uses always the same number of relayed Bundles to deliver one Bundle, the proposed scheme needs less transmissions than typical DTN protocols. Our proposition uses more relayed messages than the Direct Delivery, since the satellites store low-priority messages within gateways to minimize the buffer overflow on satellites. Other protocols, being replica-based, relay more messages to achieve the same delivery performance.

These results show that for a hybrid LEO satellites and WSN architecture, replica-based routing protocols are not required and our forwarding-based proposition with a specific scheduling achieves same or even better performance at lower relaying costs.

Finally, our proposal, Carreau, uses as few resources as the forwarded-based scheme and provides performance close or better than well-known replica-based routing protocols. Then providing priority to Bundles with greatest lifetimes as usually done in DTN is not a good option for a data mule-like scenario.

V. CONCLUSIONS

We propose a mechanism, Carreau, aiming at reducing losses during a crisis by spreading losses over time. We consider a wildfire monitoring scenario with delivery constraints to validate this mechanism. We provide an original method to solve the problem by considering ground stations as additional satellite memory. From this model, we derived a scheduling policy for the satellites and rules for the transmission of Bundles. We used the delivery ratio and the required resource in terms of relayed messages as metrics to compare our proposition with several reference DTN routing protocols. We were able to show that our proposition allows the adaptable architecture to achieve high performance with low-resource

use. The performance of one flow is enhanced while the overall performance achieves slightly comparable results with the one provided by recognised DTN solutions.

As a perspective of this work, we are currently working on an implementation of a protocol which gives priority to critical Bundles and moreover provides fairness amongst flows. The determinism of satellite delays could be exploited to reduce the mean delay. A Bundle whose destination is reached faster by another satellite than the one in the line of sight, could wait. Nevertheless, such a policy would be non work-conserving and the performance might be degraded.

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