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Power and Bandwidth Effective Data Communications in Disaster Relief Operations through a Satellite-based Disruption Tolerant Network Paradigm

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Abstract — **Providing effective telecommunication infrastructures for disaster relief and emergency operations can be achieved by taking advantage of anywhere-anytime communication capabilities offered by satellite and wireless technology. In this perspective, designing a network architecture able to ensure reliable and timely delivery of data, and able to resist against link disruption is of utmost importance. To this end, this work proposes a mobility-aided routing strategy, derived from other proposals, that aims at delivering data to destinations by taking into account power consumption issues. The efficacy of the proposed solutions is assessed by simulation, considering different scenario configurations.**

Index Terms – **Satellite Communications, Delay Tolerant Network, Routing Algorithms, Power Consumption.**

I. Introduction

OVER the last years, the scientific community has increasingly concentrated its attention on the design of network infrastructures tailored to carry out disaster relief and emergency operations in areas, where harmful natural events, such as tsunami, earthquakes, and volcano eruptions have happened. Typically, in these hazardous conditions, deploying wired network architectures able to adapt to the environment characteristics and to support effectively relief operations is not a viable approach. To tackle these networking and communication challenges, the advantages jointly offered by satellite and wireless technologies open the doors to deploying a more efficient telecommunication infrastructure, made up by integrating heterogeneous networks [1]. From the one hand, wireless technology helps design mobile networks, by taking advantage of improved routing strategies and medium contention techniques. On the other hand, the intrinsic capabilities of multicast/broadcast communication offered by satellite technology allows ubiquitous and anytime data communications.

From this overview, it is immediate to see that integration of heterogeneous technologies is fundamental to guarantee data communications in such theatres, by taking advantages of the communications benefits that wireless and satellite may bring. Nevertheless, the advantages offered by the aforementioned technologies are not sufficient to ensure effective data communications, because the high mobility of nodes along with the hostile environment peculiarities is likely to give rise to unpredictable link interruptions. To tackle part of these challenges, a disruption tolerant network architecture can be suitable to ensure robust data communication [2].

This work takes as reference a typical disaster relief theatre, where groups of nodes move through a vast area and communicate by means of 802.11 radio interfaces and by taking advantage of opportunistic contacts with Aerial (e.g., Helicopters) and Ground Vehicles (e.g., trucks, emergency vehicles). In order to guarantee larger network coverage and support for broadband services, satellite links and WiMAX segments are considered as well. The mobile nodes take advantage of all of these communication facilities such as to effectively distribute information to destinations. This paper copes with these issues and proposes an effective delivery mechanism, exploiting erasure codes and multipath routing strategies properly designed for this specific environment. In addition, also power consumption issues are addressed as, being wireless nodes mostly involved in these scenarios, the power waste can seriously limit battery lifetime. In order to account for these aspects, the routing strategy implements a Dijkstra-based algorithm, aimed at minimizing a cost function depending upon both data delivery time and network resource usage. Moreover, comparison with other techniques based on the same concepts is provided, in order to identify the advantages and the inefficiencies of this proposal and to draw next directions of this work.

The remainder of this paper is organised as follows. Firstly, a summary of related works focusing on mobility-aided routing strategies and data communications performed in complex environment is presented. Afterwards, details about the reference scenario and specifics of models used in simulations are given. Then, the proposed routing solutions, based upon erasure coding strategies and minimization of a cost function accounting for data delivery time and network resource usage, are considered. Finally, attention is paid to the performance analysis and conclusions about the effectiveness of each tested solution are drawn in order to identify the best solution for the different scenario configurations explored.

II. Related Work

Improving effectiveness of data delivery in Mobile Area Networks (MANETs) has been extensively investigated in the last years, by taking particular attention on networking issues. In this view, the case of disruption tolerant networks has been investigated [3], by studying proper data transmission strategies tailored to challenging environments by means of mobility-aided routing (MAR) schemes and erasure coding techniques, implemented at the higher layers of the protocol stack. In this view, *Ref.* [4] proposes an optimisation framework to derive optimal routing decisions based on Dijkstra algorithm, by taking advantage of contact history and topology knowledge, provided by proper "oracles", while *Ref.* [5] proposes the use of estimation techniques to predict future contacts on the basis of past encounters. The advantages offered by erasure codes are explored in [6], by paying attention on portfolio theory findings, whose application in the context of disruption tolerant networks proved to be promising. *Ref.* [7] investigates in more detail the use of erasure codes to improve the performance of routing algorithms, by fully exploiting the effectiveness of error correcting codes along with appropriate packet interleaving schemes. Considerations about improved algorithms relying upon utility functions are drawn in [8], while performance considerations of multi-copy routing protocols are contained in [9].

The design of routing schemes tailored to the peculiarities of this hazardous environment has to take into account also the networking challenges deriving from the fact that contact durations are short and rescue operations encompass a number of heterogeneous communication technologies that need to be suitably integrated. In particular, broadcast and large geographical coverage facilities offered by the satellite technology are attractive [10]; besides, recent deployments of access networks based upon WiBRO and WiMAX technologies [11-12] show significant advantages in terms of broadband communication capabilities.

Finally, in disaster relief operations, the presence of Aerial and Ground Vehicles (AVs and GVs) such as helicopters, trucks and emergency vans plays a crucial role [13] due to their ability to opportunistically exchange data with terrestrial mobile nodes, by means of radio interfaces. In addition, the presence of special relay nodes, responsible for data forwarding operations and equipped with large storage units, may further improve the overall system performance. This aspect is explored in [14], where the advantages deriving from the use of these "throwbox" nodes are pointed out.

III. The Reference Scenario

As mentioned in the previous section, this work is aimed at investigating performance of mobility-aided routing strategies suited to disruption tolerant networks, where relief operations are expected to be performed. From this point of view, taking as reference a scenario that could reproduce reliably a typical disaster relief scenario it is fundamental to infer correct indications on the overall system performance. To this end, the environment here considered is composed of mobile nodes (MNs), organised in groups, AVs, GVs (throwboxes), and satellite stations. The transmission facilities and mobility issues arising for all of these elements are outlined in the following. The overall scenario is depicted in Fig. 1.

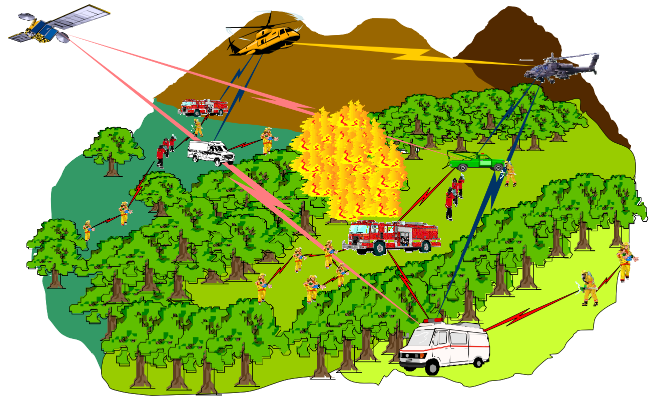

Fig. 1. The emergency theatre considered in the work

IV. The Proposed Solution

As pointed out in [3] and [6], environments exhibiting frequent link interruptions pose a number of challenges in the design of routing strategies suited to reliably transport data from source to destination nodes. In this case, routing schemes based on some knowledge of how node contacts and network topology vary over time can be exploited in order to identify the best path connecting source and destination. In particular, it is possible to classify these schemes into source-based and per-hop routing [4]. In the former, the path is computed at the beginning of any data transfer, while in the latter it is computed hop by hop, by taking advantage of knowledge about duration of node contacts and buffer availability. In both cases, routing decisions are taken by applying the Dijkstra algorithm, properly modified in order to take into account that network topology is time-variant. These classes of solutions are taken in this paper as reference and henceforth referred to as SR (Source Routing) and PH (Per Hop).

In addition, reliable data communications can be achieved also by applying adequate routing strategies jointly with erasure codes [7], in order to contrast efficiently disruptions and make data communication more robust against link errors. The first task can be fulfilled by adopting aggressive multi-hop routing techniques, consisting in distributing redundancy and information packets over different paths in order to increase the probability of correct data delivery to destination. The second point can be satisfied by taking advantage of powerful coding techniques, able to recover from severe packet losses. This approach, taken from [7], is considered in the following as a viable solution for ensuring reliable solutions and it is henceforth referred to as HEC (Hybrid Erasure Coding). It is worth relevant that all these routing solutions are aimed at minimizing delivery delay, by defining an appropriate routing cost function, being minimized by Dijkstra algorithm. This cost function will be hereafter referred to as $C_{routing}^{old}$, in order to distinguish the "old" cost formulation from those proposed here and shown in the following.

Furthermore, a forwarding strategy accounting for power consumption as well is proposed here, by looking into different schemes. Basically, the cost function used in the routing problem formulation is extended such as to incorporate also the energy actually wasted by wireless nodes during operations. By identifying "tx", "rx" and "idle" as the states in which a node transmits, receives data and listens to the channel, respectively, a possible formulation of the energy cost is as follows:

$$C_{energy} \triangleq (P_{tx} + P_{rx} + P_{idle}) \cdot \frac{PktSize}{B} \quad (1)$$

where P_{tx}, P_{rx} and P_{idle} denote the power used in "rx" state by the next hop node, in "tx" and "idle" states by the transmitting node, respectively, while B and PktSize refer to the wireless link bandwidth and the size of packet being forwarded. It is immediate to see that energy is approximately computed as product of power and packet transmission time [15].

As a result, five different approaches are proposed as follows, by considering different variants of the routing cost function, henceforth referred to as $C_{routing}^{scheme}$, where "scheme" denotes the specific strategy.

A. Pure Energy Consumption (PEC)

In order to take into account power limitation imposed by wireless network interfaces, the routing strategy is expected to select the next hop to which data will be forwarded on the basis of the minimum energy required by this operation. To this end, the routing cost function is modified as follows:

$$C_{routing}^{PEC} \triangleq \alpha \left| C_{energy} \right|^2 \quad (2)$$

where α is a normalisation constant introduced to have non-dimensional cost function.

B. Additive Delay and Energy Consumption (ADEC)

Trying to minimize both delivery delay and power consumption is expected to lead to high performance communications. To this aim, the cost function is modified by adapting concepts drawn in [16]. In practice, the cost paid to forward data from one node to next hops is evaluated as weighted sum of latency and transmitted data packets, under the assumption that the number of transmissions is a good representation of energy consumption:

$$C_{routing}^{ADEC} \triangleq C_{routing}^{old} + \beta \cdot Pkts \quad (3)$$

where β is a normalisation constant introduced to have non-dimensional cost function.

C. Additive Square Delay and Energy Consumption (ASDEC)

The formulation is very similar to ADEC. The main difference is that the energy consumption is evaluated in terms of the energy cost and additive square cost function is adopted, as follows:

$$C_{routing}^{ASDEC} \triangleq \left| C_{routing}^{old} \right|^2 + \delta \cdot \left| C_{energy} \right|^2 \quad (4)$$

where δ is a normalisation constant introduced to have non-dimensional cost function. This formulation should be able to capture the effects of real energy consumption as well as to account for delivery latency.

D. Additive Square Delay, Energy and Congestion Control (ASDEC+)

Also congestion control in disruption tolerant networks is an important point, because implementation of store-carry-forwards mechanisms may lead to performance collapse as a consequence, on the one hand, of limited node storage capacity and, on the other hand, of lengthy link disruption periods. To take this issue into account, ASDEC formulation is extended in order to include also a "buffer cost". From a mathematical viewpoint, the expression of the buffer cost is given as follows, where different expressions are considered in dependence on the amount of space already allocated to store data. It yields:

$$A \triangleq (C - S)$$
$$C_{buffer} \triangleq \begin{cases} \varphi_1 \cdot A & \text{if } S < \gamma_1 \cdot C \\ \varphi_2 \cdot A & \text{if } \gamma_1 \cdot C \le S < \gamma_2 \cdot C \\ \varphi_3 \cdot A & \text{if } S \ge \gamma_2 \cdot C \end{cases} \quad (5)$$
$$C_{routing}^{ASDEC+} \triangleq \left| C_{routing}^{old} \right|^2 + \mu \cdot \left| C_{energy} \right|^2 + \eta \cdot \left| C_{buffer} \right|^2$$

where C and S denote the capacity and available space of buffer, respectively; hence A is the space already used to store packets. Again, φ_i and γ_i, $\forall i \in \{1,2,3\}$, are weights introduced to have different buffer cost as function of the available buffer space. Finally, μ and η are normalisation constants introduced to have non-dimensional cost function.

Finally, by taking as reference the aforementioned cost definitions, five routing strategies ("cost function"- "routing strategy") are devised accordingly: SR-PEC, SR-ADEC, PH-ASDEC, PH-ASDEC+ and HEC-ASDEC.

V. Performance Analysis

A. The Testbed Configuration

The assessment of routing strategies proposed in this work, namely SR-PEC, SR-ADEC, PH-ASDEC, PH-ASDEC+ and HEC-ASDEC, was performed by having in mind a typical emergency scenario. In more detail, we considered a forest environment extending over a square area of 2500 x 2500 meters, populated by 50 mobile nodes (MNs, rescue agents), 20 GVs (ambulances and other trucks), 4 satellite stations and 1 AV (helicopter); MNs are in turn subdivided into 10 groups (relief teams). From the communication point of view, wireless links are subject to degradation, resulting from the environment peculiarities (e.g., free-space, foliage, forest attenuation, and background thermal noise). As a result, the total attenuation (A_{tt}) can be expressed as $\frac{(4\pi r)^2}{\lambda^2} \cdot A_{tree} \cdot A_{foliage}$, where first terms accounts for the free-space loss (λ is the wavelength at which radio transmissions are performed and r is the distance between the transmitting and receiving nodes), while $A_{tree} \cdot A_{foliage}$ accounts for environments peculiarities. Different values of A_{tt} were considered, ranging from 100 dB to 130 dB.

MNs move accordingly to the Virtual Track Mobility Model (VTMM) [17], suited to reproduce group mobility in military and emergency scenarios. Nodes move with a variable speed, uniformly distributed between 0 and 12 m/s.

From the communication point of view, MNs are equipped with 802.11b wireless interface and can transmit data at 1Mbit/s. Power consumption issues and maximum radio range coverage are taken into account by considering specifics of a Lucent IEEE 802.11 WaveLAN card [14]. As MNs can serve also as relay nodes, storage capacity has to be taken into account: a buffer of 256 Kbit is assumed in this work. AV flies at 40 m altitude at a constant speed of 16m/s, following the "stochastic billiard" model [18] that seems adequate to characterise AV mobility. It can receive and transmit data at 500Kbit/s to nodes within a radio range of 300m by means of 802.11 wireless interfaces. GVs, stationed in fixed positions, can take advantage of two wireless network interfaces, built on 802.11b and 802.16 technologies, allowing to transmit data to nodes within distance of 150m and 1000m, respectively. In more detail, the former guarantees exchange of data with MNs, AV and satellite stations, while the latter with GVs and satellite stations. Finally, data are transmitted by the 802.11 interface at 1 Mbit/s, while 802.16 wireless network interfaces offers a bandwidth of 10 Mbit/s. As far as satellite stations are concerned, they ensure data exchange with other nodes, by means of 802.11b wireless network interfaces offering a bandwidth of 1Mbit/s, and a connection with a geostationary satellite platform working in Ka band and offering a bandwidth of 1 Mbit/s. AV, GVs and satellite stations can work as relay stations as well. Their buffer capacity is assumed equal to 2560 Kbit (i.e., ten times MNs capacity).

Wireless nodes are enabled to generate data packets grouped in traffic flows, one for each source. Packet size is set to 1024 bytes. For the sake of the completeness, attention was paid also on how traffic load may impact on routing protocol performance. In practice, cases of *low*, *medium* and *high* traffic load are explored, by considering data flows in the number of 5, 10, 20 respectively, corresponding to a global traffic of about 5, 10 and 20Mbytes, respectively.

Finally, in order to evaluate the performance expected for each proposed protocol, their effectiveness in terms of delivery latency and reliability is tested by taking into account energy consumption as well. In more detail, two metrics suited to capture these two points are considered:

- Energy-aware delivery delay (EADD)
- Energy-aware delivery reliability (EADR)

The former is defined as ratio between the goodput (the number of bytes correctly received over the delivery time) and the energy consumption. In essence, this metrics gives indications on the cost necessary to pay, in terms of energy, such as to attain a specific level of goodput; hence, it gives an insight into effective network resource usage. In maths, it means:

$$\text{EADD} = \frac{\text{Total received bytes}}{\text{Delivery time}} \cdot \frac{1}{\text{Energy Consumption}} \quad (6)$$

The latter is expressed as ratio between the delivery factor (the number of bytes correctly received over the number of bytes generated by source nodes) and energy consumption. This metrics shows how much energy is required in order to ensure a specific level of reliability. In maths, it means:

$$\text{EADR} = \frac{\text{Total received bytes}}{\text{Total generated bytes}} \cdot \frac{1}{\text{Energy Consumption}} \quad (7)$$

The performance analysis has been conducted by means of the dtnsim simulation framework [19] adapted to the specifics of the environment investigated in this work.

A number of runs sufficient to obtain a width of the confidence interval less than 1% of the measured values for 95% of the cases is imposed, while a simulation time of 2000s is set for each test.

B. The Results

Low Traffic Load. In the case of low traffic load (5 flows carrying a total of 5Mbytes), PH-ASDEC+ and SR-ADEC offer the most satisfactory results in terms of both EADD and EADR metrics. In this configuration, we pay attention only on EADD, as EADR does not offer much more insight into the system performance. In particular, it is possible to observe from Fig. 2 that the performance is only partially affected by wireless channel attenuation (indicated in the graphs as Att), owing to the effective routing cost functions implemented. As attenuation further increases (> 125 dB), the EADD values, decrease sharply because unreliability of the transmission means makes ineffective also routing strategies specified in PH-ASDEC+ and SR-ADEC.

As far as HEC-ASDEC is concerned, it is noticeable that it offers very poor performance in consequence of the erasure codes applied in this proposal. In fact, this approach is not able to offer acceptable results since transmission of redundancy packets, on the one hand, counteracts the negative effect of the wireless link attenuation, but on the other hand implies congestion events on next hop nodes. In the case of SR-PEC and PH-ASDEC, registered values for EADD and EADR are satisfactory as long as "Att" is below 122 dB; afterwards, the performance decreases rapidly.

Medium Traffic Load. When a medium traffic load (10 flows carrying a total of 10 Mbytes) is injected into the network, considerations similar to low traffic load still hold. PH-ASDEC+ and SR-ADEC are the most promising solutions, HEC-ASDEC offers poor results, while SR-PEC and PH-ASDEC give intermediate performance. Main difference concerns numerical values registered for EADR, if compared to the previous configuration. EADR drops from 0.04 to 0.02 in consequence of the larger number of flows present in the network. In practice, the traffic load causes severe congestion events on next hop nodes, implying reduction of delivered packets, thus reducing EADR values.

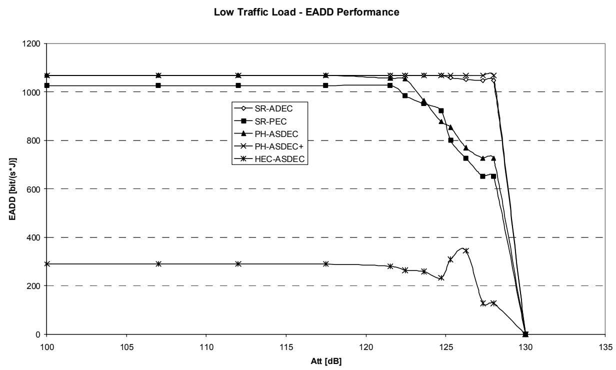

Fig. 2. EADD Performance under low traffic load

High Traffic Load. As traffic load increases even more (20 flows carrying a total of 20 Mbytes), two important facts can be stated (only EADR is reported, in Fig. 3). Firstly, also in this case, PH-ASDEC+ and SR-ADEC show their performance supremacy with respect to other solutions. On the other hand, a difference between SR-PEC and PH-ASDEC can be shown. It results from the implementation of SR-PEC that essentially accounts for energy consumption, but is not able to manage effectively the delivery delay.

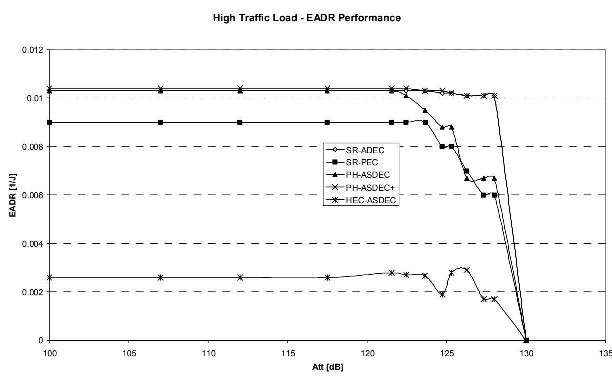

Fig. 3. EADR Performance under high traffic load

It can be noticed that HEC-ASDEC, regardless of load configuration, has an oscillatory behaviour in correspondence of attenuation values around 125 dB. This is due to the effect of erasure codes that are able to make communication more robust against link errors but cause congestion events as in this case. In practice, these two combined effects give rise to oscillations that disappear as soon as attenuation gets over 125 dB, where erasure codes are no longer effective

VI. CONCLUSIONS

The study developed in this work addressed the performance evaluation of communications performed in satellite-based disruption tolerant networks in support of disaster relief operations. In this view, two protocol proposals PH-ASDEC+ and SR-ADEC emerged as promising candidates, able to provide very good performance in terms of delivery delay and energy usage, expressed in terms of EADD and EADR metrics. In particular, conducted tests showed that benefits brought by erasure codes can be exploited only when the channel degradation is not too severe; otherwise, a larger number of redundancy packets will be required, resulting in extra-waste of power and thus in performance degradation.

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