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Advanced Hybrid Satellite and Terrestrial System Architecture for Emergency Mobile Communications

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Emergency situations require reliable broadband communications systems which are able to transmit relevant information from the disaster site to the decision makers and send feedback to first responders regarding potential dangers or decisions. A key factor in designing a robust communications system with applications to emergency response is the development of a quick, easily deployable and mobile infrastructure, providing voice and data communications, available within the first 24 hours - the most critical phase for crisis operations. In this paper, an advanced hybrid satellite and terrestrial system for emergency mobile communications, that is quickly deployable and dynamically adaptable to disasters of any nature and location, is proposed as a potential solution to the above requirements. The overall architecture is IPv6-based and we present and emphasize the important role of Vehicle Communication Gateways (VCGs) in the system. Thanks to the satellite and wireless interfaces, VCGs are able to connect via satellite the disaster area with the headquarters, to create an inter-vehicular mobile ad-hoc mesh network in the emergency field and to provide connectivity to isolated IPv6 cells. Two types of VCGs are envisaged from a satellite interface point of view, S-UMTS vehicles operating in L or S band and nomadic DVB-RCS vehicles operating in Ku or Ka band.

I. Introduction

IN many unexpected critical situations caused by natural disasters, such as hurricanes and earthquakes, or by terrorist attacks, such as the attacks of 9/11, the efficiency and safety of the responders' mission heavily rely on information technologies. Usually, the destruction, or extremely limited availability, of the communications infrastructure of the region in distress affects the rescue and recovery operations. Voice services, used to communicate among responders and with headquarters for control and command, or used by those affected by the emergency situation, may be severely restricted and unreliable even when available. Furthermore, often it is impossible to share and use all the relief resources through advanced information technologies, such as accessing remote databases, web sites and web-based applications, and exchange data with agency headquarters and other field command centers. A new set of communications tools is required to significantly improve the safety of responders and the effectiveness of rescue and recovery operations.

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To design a new architecture for public safety and disaster recovery applications and to assess its suitability, it is necessary to consider this application domain's specific requirements. The following are a set of common well-known requirements that public safety and disaster recovery communication systems must meet [1]:

- **Rapid deployment**: planning must be on the fly as minimizing the number of fatalities can be time-dependent, and a formal planning process is not feasible. Deployment process must be simple and secure so that highly specialized personnel and complex procedures are not required. Equipment must be tolerant of faults and capable of rapid deployment, which involves rough treatment due to the short timeframe required for rescue operations.

- **Interoperability**: first responders must be equipped with devices capable of using different technology by choosing the appropriate interface card and still working together to form a mesh network and communicate data. Therefore, regardless of what technology each individual might use, they must be able to uniformly connect to the relaying mesh nodes and to exchange data. Interoperability of communication devices within and across different agencies and jurisdictions is a top priority. An IP-based network is therefore the ideal common platform for communication between multiple emergency response services and different jurisdictions.

- **Robustness and reliability**: communication systems for crisis management and disaster recovery must be able to function in potentially adverse and hostile environments. The infrastructure must be sufficiently flexible and reliable to satisfy a variety of situations and provide support for different types of users, as well as for operations in different environments.

- **Scalability**: there are two types of scalability requirements: horizontal scalability refers to the network's ability to grow efficiently and cost-effectively in terms of geographical coverage, while vertical scalability stands for the ability to efficiently support an increasing number of users. Suboptimal deployment and a frequently changing environment challenge network functionality. Therefore, the network must be able to report environment changes for proper management or be self-manageable to avoid service disruption.

- **Mobility support:** in order to help emergency personnel to concentrate on the tasks, the emergency network must be mobile, deployed easily and fast with little human maintenance. Therefore, devices must be capable of automatically organizing into a network. Procedures involved in self-organization include device discovery, connection establishment, scheduling, address allocation, routing, and topology management. Public safety users must have access to constant communication while traveling at reasonable speeds. The mobility requirement includes the ability to roam between different networks, potentially operated by different agencies and jurisdictions.

- **Voice and data service support:** voice and data are the two main service categories required for public safety communications. Even though we could consider voice just another data service, it has to be treated as a separate category due to its primary role in first-responder communications. Also interactive data services should be supported, including instant messaging and video conferencing. Further requirements are Internet connectivity and support for Web-based services. The system should also be able to support real-time transmission of vital statistics of objects or persons and non-interactive data services including email and file transfer. Quality of Service (QoS) support is very important in the system. It should be able to differentiate between traffic of different priority levels because high-priority traffic should get precedence to guarantee delivery of urgent messages in case of network congestion.

- **Security:** large scale disasters require responses from multiple federal, state and local agencies with different charters and possibly also from military forces. A tremendous amount of sensitive data in the network could be exposed to the transmission media and should be appropriately protected.

- **Cost:** the network should incur reasonable cost for deployment and maintenance, and off-the-shelf technologies should be adopted to the maximum extent possible.

Taking into account all above functional and performance requirements and the fact that satellite networks are the best and more reliable platform for communications in emergency scenarios for providing a backhaul connection to the intact network infrastructure, we propose a new advanced hybrid satellite and terrestrial system architecture. It provides, at once, full mobility in the disaster site to rescue teams and broadband connectivity inside the disaster network and with headquarters. The proposed architecture is quickly deployable and dynamically adaptable to disaster of any nature and location. It is IPv6-based and able to support IP interoperability with terminals belonging to different administrators and technologies. As, generally, the deployment of Public Safety units makes use of two entities, vehicles and Public Safety users equipped with satellite and radio terminals, we have decided to implement them in the proposed hybrid satellite and terrestrial system architecture. It allows Public Safety units to move on the crisis site and to communicate urgent information among devices in the field and from devices to Internet and headquarters. This is achieved by having the different entities organize themselves into a decentralized, flat and distributed network, thus forming a mobile ad-hoc mesh network at the disaster site, a structure which enables any entity to easily reach the headquarters.

The most important and central role of the presented system architecture is played by Vehicle Communication Gateways (VCGs). They have double functionalities as shown in Fig. 1. On one side, VCGs provide vehicle-to-infrastructure (V2I) communications maintaining Internet connectivity with the disaster site through satellite links: S-UMTS vehicles operating in S/L band and DVB-RCS vehicles operating in Ku/Ka band. On the other side, VCGs are able to establish vehicle-to-vehicle (V2V) communications based on ad-hoc networking [2], giving connectivity to mobile terminals through the mobile ad-hoc mesh network.

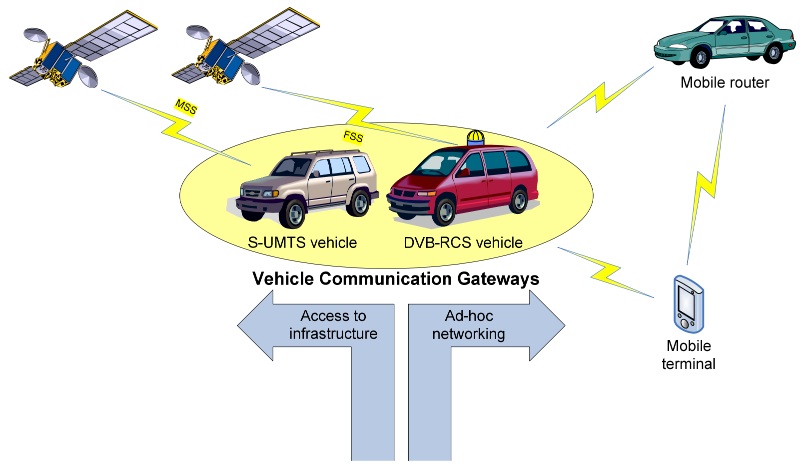

Figure 1. Vehicle Communication Gateways

II. Hybrid satellite and terrestrial system architecture

Disasters are unplanned and unexpected, and they involve loss of lives and infrastructures. The impacted community might receive several days' notice or not all; the disaster may affect a locality or could spread or cascade to affect larger areas. Thus, it is important to design a system architecture that could easily adapt to all different scenarios' configurations and to properly manage the network deployment phases that follow a hazard.

Figure 2 presents a general overview of the proposed system architecture for emergency mobile communications. It consists of:

- A space segment which includes two GEO satellites, one MSS and one FSS;
- A terrestrial infrastructure segment which includes two Earth stations connected through the Internet to the headquarters, providing the link between the satellite system and satellite terminal segment deployed in the disaster site;
- A terminal segment which includes:
  - A satellite terminal segment composed of:
    - User terminals such as satellite phones that provide direct satellite access to end-users;
    - VCGs that provide satellite access to terrestrial user terminals and mobile routers;
  - A terrestrial terminal segment that includes:
    - End-user terminals such as handhelds, PDAs, PCs;
    - Vehicular terminals that provide access to the terrestrial end-user terminals and are enabled with routing capabilities, they form a mobile ad-hoc mesh network over the crisis area.

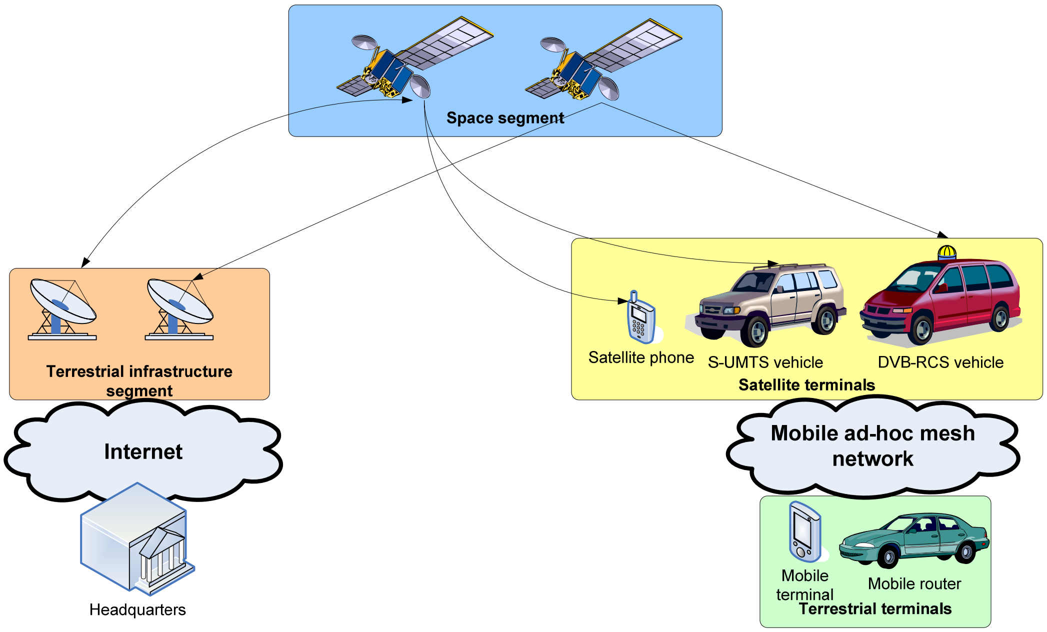

Figure 2. General overview of the advanced system architecture

When a disaster occurs, two different and consecutive phases can be identified for the network deployment of rescue teams in the disaster area. The first phase is characterized by Public Safety vehicles moving to the crisis site and reaching the most critical areas of the disaster. Although the mobile ad-hoc mesh network can provide situational awareness for the nodes within its network, mobile backhaul communications capabilities are required to distribute that information to the decision center. As shown in Fig. 3, S-UMTS vehicles provide a mobile communications solutions through S/L band between the mobile ad-hoc mesh network at the disaster field and the Internet backbone where the fixed decision center is situated. Thus, logistic information can be collected locally within the ad-hoc mesh network, then transported via Mobile Satellite Service (MSS) and aggregated to provide a Common Operational Picture (COP) to the decision center.

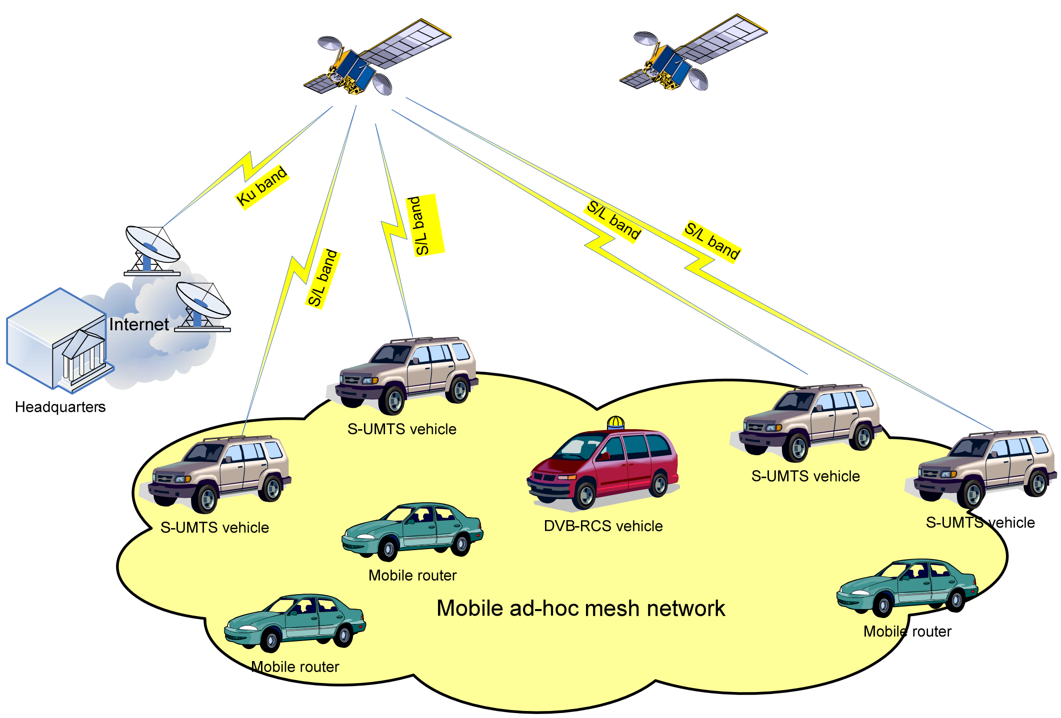

Figure 3. Hybrid satellite-terrestrial system architecture – Network deployment phase 1

In the second phase, once vehicles have reached critical areas, pedestrian Public Safety units start the rescue operations. As shown in Fig. 4, Wi-Fi and ad hoc networks are created by mobile terminals and connected to the ad-hoc mesh network through the closest mobile router. The mobility in the crisis field decreases in this phase. Transportable terminals, like DVB-RCS vehicles, working on-the-pause or at very low speed, provide the benefit of high throughput and efficient bandwidth utilization. In addition, S-UMTS vehicles can be used to give external connectivity to groups not reached by the mobile ad-hoc mesh network.

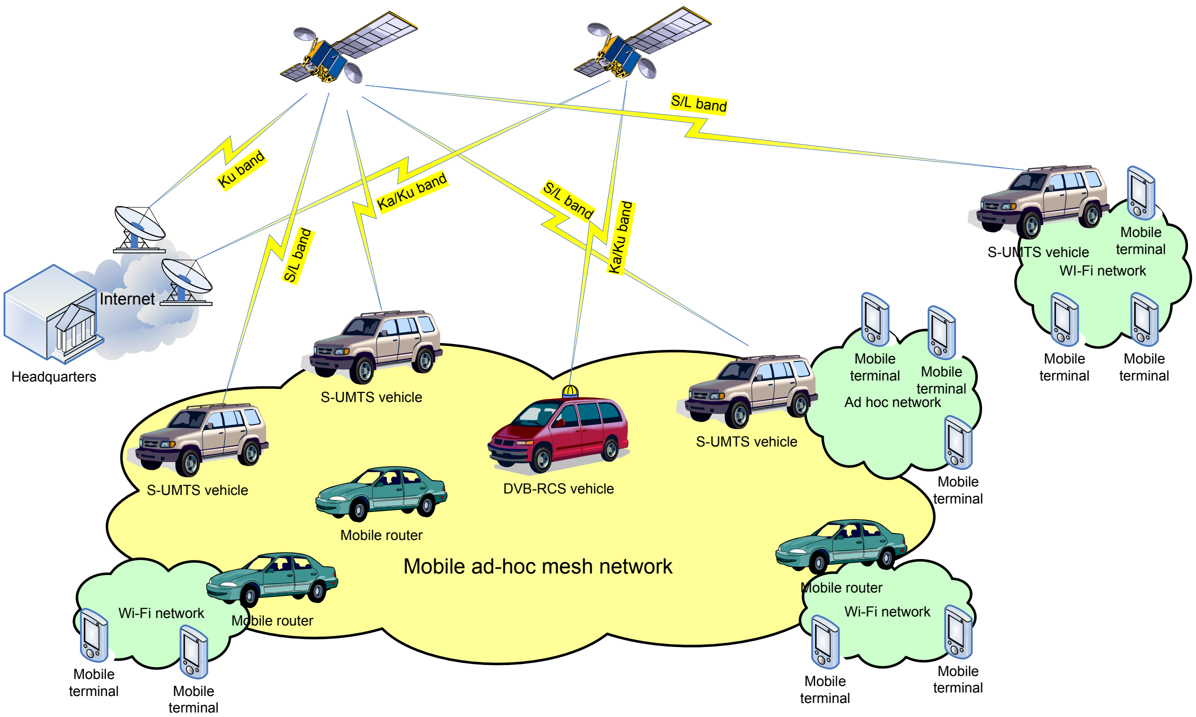

Figure 4. Hybrid satellite-terrestrial system architecture – Network deployment phase 2

For both phases, a key role is played by the ad-hoc mesh network. It is a multi-hop wireless network with self-healing and self-configuring capabilities; it is dynamically self-organized, with the nodes in the network automatically establishing an ad hoc network and maintaining the mesh connectivity. The proposed mobile ad-hoc mesh network represents an enhancement to the standard ad hoc networks as it has the following characteristics [3]:

- *Wireless infrastructure/backbone:* the ad-hoc mesh network consists of a wireless backbone with mesh routers. It provides large coverage, connectivity and robustness in the wireless domain. The connectivity in ad hoc networks depends on the individual contributions of end-users which may not be reliable.
- *Integration:* the ad-hoc mesh network supports conventional clients that use the same radio technologies as a mesh router. This is accomplished through a host-routing function available in mesh routers. It also enables integration of various existing networks such as Wi-Fi, the Internet, cellular and sensor networks through gateway/bridge functionalities in the mesh routers. Consequently, users in one network are provided with services in other networks, through the use of the wireless infrastructure. The integrated wireless networks through the ad-hoc mesh network resemble the Internet backbone, since the physical location of network nodes becomes less important than the capacity and network topology.
- *Dedicated routing and configuration:* in ad hoc networks, end-user devices also perform routing and configuration functionalities for all other nodes. However, the ad-hoc mesh network contains mesh routers for these functionalities. The load on end-user devices is significantly decreased, which provides lower energy consumption and high-end application capabilities to mobile and energy constrained end-users. End-user requirements are limited which decreases the cost of devices used in the ad-hoc mesh network.
- *Multiple radios:* mesh routers can be equipped with multiple radios to perform routing and access functionalities. This enables separation of two main types of traffic in the wireless domain. While routing and configuration are performed between mesh routers, the access to the network by end users can be carried out on a different radio. This significantly improves the capacity of the network. On the other hand, in ad hoc networks, these functionalities are performed in the same channel, and as a result, the performance decreases.

III. V2I communications: satellite links

A. S-UMTS vehicles

The use of narrowband, such as L or S band, has encountered such a success in emergency mobile communications that it cannot be ignored in a disaster system scenario definition as it allows high mobility in the disaster site and low cost antennas and terminals. S-UMTS vehicles can be used immediately after a disaster and if all available MSS capacity is combined together and shared between all users, it can also provide external broadband connectivity. S-UMTS vehicles can reach areas far from the mobile ad-hoc mesh network and rapidly bring V2I connectivity to isolated Wi-Fi or ad hoc networks. Moreover, narrow band allows developing mobile terminals which serve as interface between the satellite and any type of terrestrial network access point (e.g. UMTS, Wi-Fi, 2G).

As regards the type of L or S band vehicular antenna installed on it, two candidate solutions in S band are presented in this work: active antenna and omnidirectional antenna. The technical specifications for the S-band link, described in Table 1, have been chosen as a baseline to characterize S-UMTS vehicles.

Link budget results show that S-UMTS vehicles with active antenna can reach data rate up to 4 Mbit/s in the forward link, and up to 80 Kbit/s in the return link. Considering the limited data rate that can be reached in the return link, the leading idea is to dynamically create a distributed gateway between S-UMTS vehicles that are in LOS for the external communications, so the effective bit rate can be higher depending on the number of vehicles used. Using CDMA and Spread Aloha access method in the return link, the data rate can reach 800 Kbit/s if at least 10 vehicles are in LOS, transmitting simultaneously as a distributed gateway. The terminal mobility for S-UMTS vehicles is around 50 Km/h.

Table 1. Specifications of S-UMTS vehicle

Category	Parameters	Active antenna	Omnidirectional antenna
RF Section Characteristics	Frequency Band	2.1-2.2 GHz	
	Antenna Diameter	0.16 m	0.09 m
	Rx G/T	- 16 dB/K	- 21 dB/K
	Tx EIRP	18.5 dBW	10.5 dBW
	Total Bandwidth	Tx: 5 MHz Rx: 5 MHz	
Downlink	Proposed Air Interface	DVB-S2	
	Modulation and Coding	QPSK 1/2	
	Waveform	TDM	
	Max data rate	4Mbit/s	
Uplink	Proposed Air Interface	S-UMTS	
	Modulation and Coding	QPSK 1/3	
	Waveform	CDMA	
	Spreading factor	32	64
	Max data rate per user	80 Kbit/s	40 Kbit/s

B. DVB-RCS vehicles

S and L band provide services as voice and data for emergency communications, but only broadband, as Ku and Ka band, can offer large capacity and high date rate necessary to exchange multimedia data such as medical data, digital map or intelligence data. In particular, Ka band has several advantages. Transportable terminals, like DVB-RCS vehicles, can benefit of broadband communications, efficient bandwidth utilization and cheap capacity. The available bandwidth is very large and not much occupied and it is possible to use small antennas for terminals as the Ultra-Small Aperture Terminal (USAT) [4]-[5] illustrated in Fig. 5, able to provide multimedia data and services.

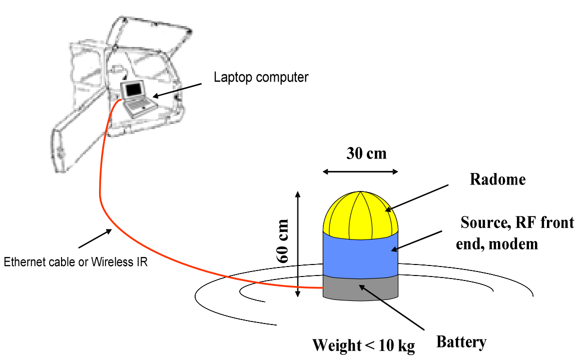

Figure 5. Nomadic terminal in Ka band

With a diameter of 30 cm and a satellite EIRP of 58 dBW, the presented DVB-RCS vehicle can receive, on the satellite downlink, data rates up to 25 Mbit/sec in temperate and desert zones and a data rate of 8 Mbit/sec in tropical zone. With a satellite G/T of 19 dB/K thanks to the Space Division Multiple Access (SDMA), it can provide uplink with a data rate up to 512 Kbit/sec in temperate and desert zones and a data rate of 128 Kbit/sec in tropical zone. The terminal mobility for DVB-RCS vehicles spans from fixed to a target speed of 10 Km/h.

IV. V2V communications: ad hoc mesh networking

The ad-hoc mesh network, which gives connectivity to isolated Wi-Fi and ad hoc networks, is the proposed communication infrastructure at the disaster site where the existing network is partially or fully unavailable [6].

It is characterized by two types of vehicles, one with routing capabilities and an other type, the VCGs, performing IP routing and gateway functionalities. Each vehicle in the disaster area is a Mesh Point (MP), establishes peer links with MP neighbors and is fully participant to the mobile ad-hoc mesh network. According to the topology configuration of the network, a MP can assume the functionality of Mesh Access Point (MAP), providing access to the mesh network to mobile terminals. VCGs are also Mesh Portal Points (MPPs), as they represent MPs through which is possible to enter and exit the ad-hoc mesh network. The topology configuration of the mobile ad-hoc mesh network is illustrated in Fig. 6.

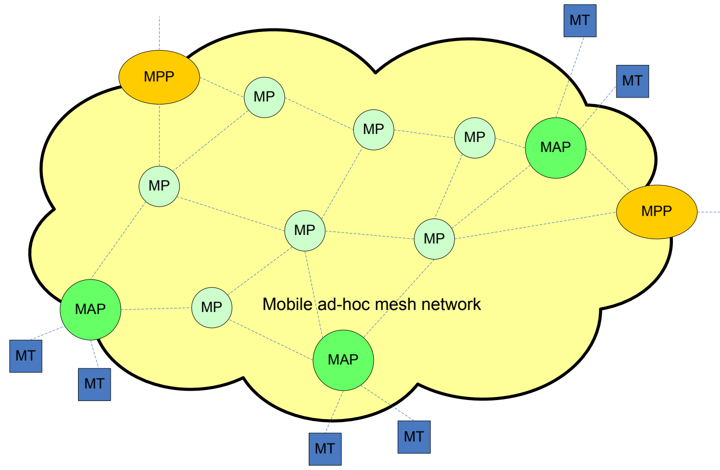

Figure 6. Topology configuration of the ad-hoc mesh network

The 802.11s WLAN Mesh Networking [7], that integrates mesh networking services and protocols with 802.11 at MAC layer, well fits the proposed architecture as it creates a Wireless Distribution System (WDS) with automatic topology learning and wireless path configuration. At the present, IEEE 802.11s is the most relevant emerging standard for Wireless Mesh Network (WMN) technology in the context of public safety and disaster recovery communications. It is in contrast to most current WMNs, which implement mesh functionality at the network layer.

The Hybrid Wireless Mesh Protocol (HWMP) [8] is the default routing protocol for IEEE 802.11s WLAN mesh networking. Every IEEE 802.11s compliant device is required to implement this path selection protocol and to be capable of using it. This allows interoperability between devices of different vendors. As a hybrid routing protocol, HWMP contains both reactive routing components as well as proactive routing components.

The foundation of HWMP is an adaptation of the reactive routing protocol Ad hoc On-demand Distance Vector (AODV) [9] called *Radio-Metric AODV (RM-AODV)*. While AODV works on layer 3 with IP addresses and uses the hop count as routing metric, RM-AODV works on layer 2 with MAC addresses and uses a radio-aware routing metric for the path selection. The on-demand path setup is achieved by a path discovery mechanism that is very similar to the one of AODV. If a MP needs a path to a destination, it broadcasts a *Path Request Message (PREQ)* into the mesh network. MPs will rebroadcast the updated PREQ whenever the received PREQ corresponds to a newer or better path to the source. Similarly, the requested destination MP will respond with a *Path Reply Message (PREP)* whenever a received PREQ corresponds to a newer or better path to the source. Intermediate MPs that have already a valid path to the requested destination, can respond with a PREP, if the *Destination Only* flag is not set. Depending on the new *Reply and Forward* flag, they can also rebroadcast the updated PREQ. This will result in a current path metric in addition to the fast path discovery.

The proactive component of HWMP is the extension with a proactive routing tree to specially designated MPs. Any MP that is configured to be a root MP, will periodically broadcast *proactive PREQ messages* or *Root Announcement Messages (RANNs)* into the wireless mesh network, which will create and maintain a tree of paths to the root MP. Depending on the configuration of this root portal, MPs that receive a root portal announcement register with the root portal or not (*registration mode* or *non-registration mode*). The created and maintained tree allows proactive routing towards MPPs. This proactive extension of HWMP uses the same distance vector methodology as RM-AODV and reuses routing control messages of RM-AODV.

Thus, the HWMP is a good path selection protocol candidate for the proposed ad-hoc mesh network as it combines the flexibility of on-demand route discovery with extensions to enable efficient proactive routing to mesh portals. This combination allows MPs to perform the discovery and maintenance of optimal routes themselves for communications in the disaster area and to leverage the formation of a tree structure based on a root node, i.e. a MPP, to quickly establish paths to the headquarters.

V. Conclusions

In this paper, a new system architecture, which supports IPv6 and can integrate hybrid satellite and wireless terrestrial networks to provide mobile emergency communications, is presented. The key objectives of the targeted heterogeneous infrastructure are the full mobility of rescue teams and the covering of bi-directional communication needs for voice and data in the first critical hours following an emergency. Two types of communications are implemented by VCGs in the advanced hybrid satellite and terrestrial system architecture: V2I communications through satellite links and V2V communications through ad hoc networking.

V2I communications are provided by the combination of narrowband and broadband, making the system architecture adaptable to all emergency mobile communications needs. S-UMTS vehicles allow high mobility and, by sharing all the external connectivity and acting as a mobile distributed gateway, can provide increased capacity (i.e. the aggregate) and reliability in the field for critical traffic to the headquarters (voice calls, messaging). DVB-RCS vehicles, equipped with a very compact and transportable terminal, can offer broadband multimedia services making use of a more robust, cheaper and reliable satellite link.

VCGs, together with mobile routers, implement V2V communications, creating a mobile ad-hoc mesh network in the disaster area. It is a multi-hop wireless network that supports ad hoc networking and has capability of self-forming, self-healing and self-organization. The proposed ad-hoc mesh network is IEEE 802.11s based and each mesh point implements the HWMP as path selection protocol. On demand routing based on RM-AODV is used by MPs to easily establish routes inside the ad-hoc mesh network, while proactive routing based on tree-based routing is used to connect the disaster area with the decision site.

Acknowledgments

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