Cognitive Radio Emergency Networks – Requirements and Design

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Abstract— **Currently deployed wireless emergency networks possess low spectrum efficiency, similar to their civilian wireless counterparts. Its due to the traditional radio frequency partitioning where each service a has uniquely assigned bandwidth. To alleviate the problem one can propose dynamic channel assignment as a promising foundation for physical and link layer design of future wireless emergency communication networks. Here we identify functional requirements and system specifications for mobile ad hoc emergency networks built on top of Cognitive Radio. We also propose a simple Cognitive Radio medium access control protocol applicable to our network model, adopted from Distributed Channel Assignment algorithm of IEEE 802.11.**

I. INTRODUCTION

Emergency ad hoc wireless networks must address much broader set of services and functions than their civilian purpose counterparts since many of the requirements arise only during rescue operations. For example in the aftermath of a severe earthquake when some parts of communication infrastructure has been damaged, emergency service workers must still communicate effectively. Emergency personnel working in the disaster site must know exact position of each other for efficient coordination of rescue operations. During emergency in a chemical factory each worker has to be advised immediately about toxic leakage through a network capable of multicasting information reliably. Any protocol used in such a network must be robust and capable of supporting heavy traffic during peaks of the activity. Network protocols must be energy efficient since most of the devices are battery powered. It is also necessary that packets carrying critical information are transported through the network with minimum latency.

Communication systems that are now available for rescue services lack crucial characteristics which are very important since human lives are at stake. For example, TETRA standard based systems [1] hardly support data communication. Further, existing commercial cellular systems that might be used by emergency personnel are not reliable enough. However the most important frailty in todays emergency networks is their spectrum scarcity [2]. Since many emergency networks occupy different frequency bands, where each band is heavily congested and exclusively available for specific group of users, cooperation between two emergency networks built on top of the same standard is impeded. Therefore to alleviate the problem of spectrum shortage we can identify dynamic spectrum access paradigm as a basis for physical and link layer design of emergency network. FCC calls this approach as *Cognitive Radio* and describes it as wireless node or network able to negotiate cooperatively with other users to enable more efficient utilization of radio resources. Cognitive Radio would be able to identify portion of unused spectrum and utilize it for communication purposes. In contrast, Mitola and Maguire [3] described it as a decision making layer at which wireless personal digital assistants and the related networks are sufficiently computationally intelligent about radio resources and related computer-to-computer communications to detect user communications needs as a function of use context, and to provide radio resources and wire less services most appropriate to those needs [4]. It is a vision of an intelligent wireless "black-box" with which user travels. Wherever the user goes, cognitive device will adapt to new environment allowing user to be always connected. Thus FCC approach is a simplified form of Mitola and Maguire's vision where only radio spectrum conditions are considered while taking decision about future transmission and reception parameters. In this work we take FCC's view of the cognitive radio and proceed with this understanding. We emphasize that Cognitive Radio may have access to either or both licensed and unlicensed bands. We also remark that other names are used as well in literature to define Cognitive Radio systems, for instance, Dynamic Spectrum Access, Spectrum Agile Radio or Opportunistic Spectrum Allocation.

Many studies covered functional and service specifications of next generation emergency networks, like MESA project launched by ETSI and TIA in 2000 [5]. Similar tasks were performed in SAFECOM project [6] in which requirements for emergency networks were stated taking into account more recent technology advancements than what was done earlier by PSWAC [7]. WIDENS [8], a MESA official liaison, focused on design of high data rate emergency networks with cooperation capabilities with existing infrastructure networks like TETRA. WIDENS network was composed of "terminoids", wireless nodes with IP capabilities enhanced by software defined radio where network structure was based on ad hoc networking. Each node utilized MIMO scheme for transmission and reception, however it suffered from static frequency allocation. IP

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Firefighter project [9] also having its roots in MESA, focused on utilizing existing IP based wireless hardware for fire fighter brigades. It consisted of personal wireless nodes built on top of IEEE 802.11 standard. Each node transmitted information about fireman position together with other data to the control center. However network reliability is questionable since it was built on top of legacy WLAN equipment and the problem of fixed spectrum allocation was unsolved.

As many projects covered requirements for emergency networks there is still a lack of focus on design issues and communication requirements for networks to support emergency services based on Cognitive Radio. This paper attempts to bring out all the aspects together with a strong perspective on using *Cognitive Radio Medium Access Control* (CR MAC). As a main result we propose a new CR MAC algorithm that covers most of the listed requirements.

The paper is organized as follows. In Section II we list communication services and system requirements anticipated in future emergency networks. Section III is devoted to the description of proposed network architecture. Requirements for CR MAC together with proposed solution of CR MAC based on Dynamic Channel Assignment algorithm designed for IEEE 802.11 networks is presented in Section IV. Finally Section V concludes the paper and throws some light on future directions.

II. SERVICES AND SYSTEM REQUIREMENTS

A. Expected services

S1 **Data messages:** Many types of data messages should be transported by wireless equipment. In emergency scenario such messages can be for example location information, building plan download, health status of rescue workers transmission to remotely monitor their health, sensor data for monitoring surrounding and special alarms transport.

S2 **Real time voice:** It allows for efficient coordination of the efforts between personnel and the commander and between local and neighboring emergency departments.

S3 **Still picture:** Still picture is useful to locate victims or suspicious elements in the surroundings. It also helps in achieving effective coordination of rescue operation.

S4 **Real time video:** Realtime video images sent from the scene are useful for surveillance, and remote medical treatment.

S5 **Remote control:** Remote control is needed in the rescue operation as an extension to human activities, for example to steer robots to access dangerous areas.

Network must support all these services but we must remark that they all have different constraints in terms of delay, jitter, packet error, loss rate and bandwidth. For example, a voice call is sensitive to delay and jitter, realtime video needs more bandwidth and data message like special alarm poses higher requirement on packet error or loss rate.

B. System Requirements

R1 **Self-organization:** In order to help emergency personnel to concentrate on the tasks, emergency network should be 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.

R2 **Reliability:** The reason for reliability is twofold. First, in emergency situations each rescue worker must neither be isolated from the command center nor from other team members. Second, mobility is likely to occur frequently in an emergency network. Thus, ability to adapt to network dynamics and harsh situations plays a major role in the design.

R3 **Scalability:** It refers to the ability of a system to support large number of parameters without impacting the performance. These parameters include number of nodes, traffic load and mobility aspects. Limited processing and storage capacities of some of the radio devices are also a concern.

R4 **Power efficiency:** It is needed to prolong battery life of each device, thus extending the lifetime of whole network.

R5 **Security:** Security is always a critical aspect during deployment of a wireless network since the broadcast nature of wireless signals and network itself is vulnerable to attacks at various protocol layers. Especially with the introduction of Cognitive Radio efficient resilience for physical layer jamming is crucial.

R6 **Multicasting:** Efficient multicast should be supported by the network. For example, in a fire incident, still picture sent from a fire fighter to the commander is a one-way point-to-point communication while voice calls between fire fighters and commander is two-way or many-to-one communication.

III. NETWORK

Our emergency network architecture consists of *Incident Area Network* (IAN), *Jurisdiction Area Network* (JAN) and *External Area Network* (EAN) [6] (see Fig. 1). IAN serves as a network created for a specific incident in a small area and is temporary in nature. JAN serves as a backbone with which IAN can access general purpose networks as well as EAN. Finally EAN contains all infrastructure networks, including PSTN, Internet, etc. In this paper, we focus on IAN, and use emergency network and the IAN term interchangeably.

Usually, rescue workers are organized into groups for operational ease. Thus equipments for communication carried by rescue personnel are also accordingly clustered into different groups. To follow this requirement Fig. 2 gives the architecture for IAN, where we classify devices into *communication node*, *group gateway* and *IAN gateway*. Each group has a gateway, which is responsible for communication with other groups or

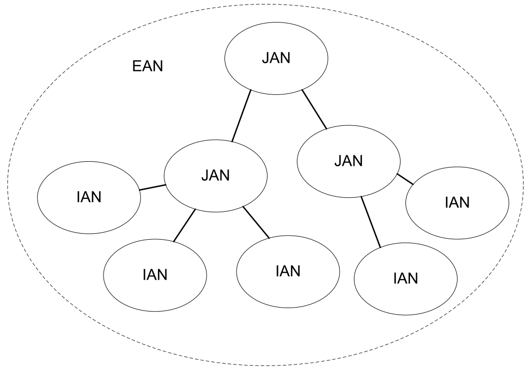

Fig. 1. Relations between proposed emergency network components; IAN - Incidence Area Network, JAN - Jurisdiction Area Network, EAN - Extended Area Network.

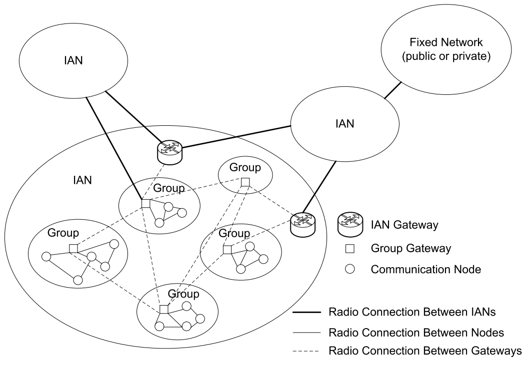

Fig. 2. Structure of Incident Area Network.

IAN gateways. Devices which have more capabilities in terms of processing power, power supply, and storage capacity are selected as group gateways. IAN gateways mainly support communication from or to IAN. They could be the same devices as group gateways, like dedicated devices or control centers which have fixed connections to backbone networks. Moreover in order to avoid single point of failure each element in the network must keep more than one connection to others.

IV. COGNITIVE RADIO NETWORK REQUIREMENTS

Ad hoc Cognitive Radio Emergency Networks differ from form normal fixed spectrum networks in many ways. Our design is driven by a set of additional protocol design requirements. Here we focus on Medium Access Control protocol design.

We use IEEE 802.11 standard MAC for ad hoc wireless networks as the basis for design since it has been endowed with much research attention presently and is also one of the most used MAC protocol in todays WLAN networks. Therefore it is pragmatic to use this model. Since nodes in a *Cognitive Radio Network* (CRN) should communicate with each other to exchange signaling information [10] through a pre-assigned common control channel, we outline the design requirements for common control channel and traffic channels distinctly.

A. CR MAC control channel

C1 **Dimensioning of control channel:** The gain from introducing more traffic channels to CRN is not linearly proportional [11] due to the fact that common control channel becomes "saturated" with signaling packets. We may construct a dynamic common control channel which will have different bandwidth depending on the number of users in all bands of CRN at any instant. One of the candidates for such a channel is UWB. We also assume that UWB channel resides in the same part of the spectrum as most of the traffic channels in CRN. Using UWB as a common control channel has a spin off that we can concurrently provide information about position of nodes.

C2 **Switching time:** Time for switching traffic channels in CRN node must be negligible and should effectively introduce no additional latency.

C3 **Half-Duplex transmission:** Each CRN node can either transmit or receive at any instant. Further it can either send or receive data or send or receive signalling. This is due to the fact that usually not every node in IAN could have full spectrum sensing capability. Full spectrum sensing capability means that nodes are equipped with two antennas – one for transmission or reception and the other for spectrum sensing or signalling.

C4 **Localizing capabilities:** We should utilize the information about position of the node in MAC protocol. If CRN nodes know exact locations of licensed bands they can always compare its position with the stored coordinates and utilize this information as one of the criteria in frequency selection process.

C5 **Multiple criterions for channel switching:** The approach here is to use cross layer information because CR MAC protocol must utilize the information from physical and link layer to assign resources for wireless nodes. Assigning resources is based on various polices. Some of those policies are spatial reuse, minimizing the use of licensed bandwidth, etc.

C6 **Sensing information distribution:** Information about the primary user of the licensed band should be exchanged even when common control channel is saturated. Each packet from a primary user of licensed band must be transported immediately to each cognitive node in the vicinity of the primary node. Designers should construct a signaling scheme in which packets with information about available licensed users must be always allowed first, no matter how many other packets are waiting in the queue.

C7 **Cooperation with legacy ad hoc equipment:** Designed MAC should allow communication between legacy equipment (IEEE 802.11 nodes) and CRN nodes. Moreover we assume that not every node in IAN has sensing capability so we have to periodically inform nodes about available channels.

B. CR MAC traffic channel

T1 **Classes of service:** In Section II we have listed many services to be supported by emergency networks. Each of these services has a specific priority which should be reflected in the CR MAC transmission.

T2 **Power control:** Synchronization complicates the design of ad hoc network. We cannot assume sleeping mode because nodes will not know when to receive beacons. One of the proposed solutions is to assign different transmitting powers to different packets. Moreover we can periodically change transmitting powers of some of the data packets.

T3 **Mobility support:** MAC protocols do not consider different types of node mobility. One of the research areas for the CR MAC is to focus on the impact of various types of mobility on elementary performance metrics (throughput, latency, etc.)

Since we have adapted 802.11 MAC to Ad Hoc Cognitive Radio Emergency Network, RTS and CTS control packets in a separate control channel will encounter less collisions (DATA and ACK packets will be transported in traffic channels). We also encounter smaller possibility of hidden and exposed terminal phenomenon.

In legacy IEEE 802.11 CSMA/CA transmission is continuous and it makes inter-packet sensing difficult. Therefore, a sender can divide data into smaller segments. Between transmission of segments each node will perform channel sensing if licensed user is already available.

We have remarked earlier that one approach for building common control channel is UWB. However it has to be noted that throughput of UWB decreases heavily with distance [12]. This would simply mean that maximal distance between neighboring nodes of CRN will be limited to UWB transmission distance. Such limitation is caused by low power levels in which UWB nodes are allowed to transmit.

C. Proposed Cognitive Radio System

We propose a new Cognitive Radio Medium Access Control which fulfills most of the requirements listed in Section IV. The algorithm utilizes two systems: *Spectrum Pooling* [13] and *Distributed Channel Assignment* (DCA) [11] – one of the multi channel extension of IEEE 802.11 CSMA/CA scheme [14]. Spectrum pooling serves as a physical layer signalling for detection of primary users, while DCA serves as a scheme for data exchange and signalling on the network layer. This is a *Peer to Peer Cognitive Radio* network in which only two nodes (receiver and transmitter) negotiate about future channel utilization.

In original Spectrum Pooling system only the access point is able to decide on licensed channels that can be used by the users. We extend this model with a distributed approach. Since in ad hoc emergency network some nodes have richer capabilities, in terms of power or battery supply, than others (see Section II-A) they can serve as Access Points deciding on which channels to use. For details on protocol for information distribution of finding primary users we refer to *Boosting Protocol* of Spectrum Pooling system [13].

All nodes in a Cognitive Radio network perform standard one-way handshake described by DCA, but decision on choosing the channel by the receiver is also based on information given by the boosting protocol. Moreover, sender-receiver pair stop their transmission or reception and again perform the channel negotiation procedure when the primary user starts using the channel which is currently used by them.

We selected DCA because it assumes availability of only two antennas (thus it has minimal requirements on size). One antenna is always tuned to appropriate traffic channel while another antenna will perform spectrum scanning and sending or receiving on control channel.

In DCA algorithm each node stores two data structures: *Current Usage List* (CUL) and *Free Channel List* (FCL). Each node stores information about utilization of every channel, marked in its CUL as available by Spectrum Pooling system. Overall number of frequency channels available for transmission depend on the activity of primary users in licensed bands – this implies that sometimes all licensed bands may be occupied. However we ensure that each node has always a minimum number of channels available for random access – its own emergency band and all unlicensed bands. We also stress that among many CR systems emergency networks will always have *preemption*. Detection of emergency service might be realized either on physical or network layer.

Such preemption is also visible in other scenarios than traditional frequency partitioning. Suppose that emergency service administrator buys a spectrum from a radio regulator (such scenario is called *spectrum trading* [15]). Then administrator might sell parts of his spectrum to other users because its bandwidth is not occupied permanently. However when bandwidth is needed emergency network will immediately take over all its bandwidth from others. We can also envision a situation when many emergency networks with distinctly assigned bandwidths cooperatively utilizing their radio resources to achieve high probability of access to free spectrum.

Each node's CUL list stores information about neighbors. For neighbor i, $CUL[i].host$ represents neighbor host address of i, $CUL[i].ch$ represents name of the utilized channel of i and $CUL[i].rel\_time$ time of channel utilization by its neighbor. A description of the algorithm is presented below (names of the parameters used in the algorithm description are presented in Table I and follow the notation from original paper).

1. **Channel conditions check from sender side**
    a) Update channel information given by Spectrum Pooling system:
        i) Add new available channels to FCL,
        ii) Remove channels from CUL which are occupied by licensed users.

    b) Check if for $CUL[i].host = sender$ $CUL[i].rel\_time > T_{curr} + T_{DIFS} + T_{RTS} + T_{SIFS} + T_{CTS}$. If condition is not fulfilled go to step 1.
    c) For all i find a channel $CUL[i].ch = D$ such that $CUL[i].rel\_time \leq T_{curr} + T_{DIFS} + T_{RTS} + T_{SIFS} + T_{CTS}$.

2. **Request to send**
    b) Perform carrier sensing on control channel and if channel is not free then go to step 1; Else:
    a) Send RTS packet containing FCL and L_d.
3. **Transmit inhibition**
    a) All nodes receiving RTS inhibit their transmission on time $NAV_{RTS} = 2T_{SIFS} + T_{CTS} + T_{RES} + 2\tau$.
4. **Clear to send**
    a) Update channel information given by Spectrum Pooling system:
        i) Add new available channels to FCL,
        ii) Remove channels from CUL which are occupied by licensed users.
    b) $\forall\ D \in FCL$ check if $CUL[i].rel\_time \leq T_{curr} + T_{SIFS} + T_{CTS}$.
    c) Pick D randomly and reply to sender with CTS containing D address and $NAV_{CTS} = L_d/B_d + T_{ACK} + 2\tau$.
    c) Receiver tunes his antenna to D.
    a) Otherwise receiver replies with CTS containing $T_{est} = min\{\forall i, CUL[i].rel_{time}\} - T_{curr} - T_{SIFS} - T_{CTS}$
5. **Waiting for clear to send**
    a) Update channel information given by Spectrum Pooling system:
        i) Add new available channels to FCL,
        ii) Remove channels from CUL which are occupied by licensed users.
    b) If after $T_{SIFS} + T_{CTS} + T_{RES} + 2\tau$ sender will receive no CTS from receiver on channel D go to step 1.
6. **Negotiation process**
    a) Update channel information given by Spectrum Pooling system:
        i) Add new available channels to FCL,
        ii) Remove channels from CUL which are occupied by licensed users.
    b) If received $CTS(D, NAV_{CTS})$:
        i) If received $D \notin FCL$ go to step 1; Else:
        ii) Update CUL such that $CUL[k].host = reciever$, $CUL[k].ch = D$, $CUL[k].rel_{time} = T_{curr} + NAV_{CTS}$.
        iii) Send RES containing D and $NAV_{RES} = NAV_{CTS} - T_{SIFS} - T_{RES}$.
        iv) Tune antenna to channel D.

TABLE I
MEANINGS OF VARIABLES AND CONSTRAINTS USED IN CR MAC PROTOCOL.

T_{SIFS}	length of short time interframe spacing
T_{DIFS}	length of distributed interframe spacing
T_{RTS}	time to transmit RTS
T_{CTS}	time to transmit CTS
T_{RES}	time to transmit RES
T_{curr}	current clock of mobile host
T_{est}	minimum time after receiver's CUL will change
T_{ACK}	time to transmit ACK
NAV_{RTS}	Network Allocation Vector on receiving RTS
NAV_{CTS}	Network Allocation Vector on receiving CTS
NAV_{RES}	Network Allocation Vector on receiving RES
L_d	length of data packet
L_c	length of control packet
B_d	bandwidth of data channel
B_c	bandwidth of control channel
τ	maximal propagation delay
D	chosen traffic channel

    c) If received $CTS(T_{est})$ go to step 1.
7. **Acknowledge**
    a) Receiver replies with ACK after receiving complete data on channel D.
8. **CTS update after RES receive**
    a) Each host receiving CTS updates its CUL such that $CUL[k].host = reciever$, $CUL[k].ch = D$ and $CUL[k].rel_{time} = T_{curr} + NAV_{CTS} + \tau$.
9. **CUL update after RES receive**
    a) Each host receiving RES updates its CUL such that $CUL[k].host = sender$, $CUL[k].ch = D$ and $CUL[k].rel_{time} = T_{curr} + NAV_{RES}$.
10. **Transmission disruption**
    a) If sender during data transmission receives signal from Spectrum Pooling system that D is occupied by primary licensed users then go to step 1.
    b) If receiver during data transmission receives signal from Spectrum Pooling system that D is occupied by primary licensed users then stop.

It must be clear that each node receives the same information from Spectrum Pooling System so FCL and CUL of each node in Ad Hoc Cognitive Radio Emergency Network contains the same information about primary licensed users availability.

With this algorithm we fulfill conditions for control channel: C1–C3 and C5–C7. We can also accomplish requirement T2 for traffic channel.

V. CONCLUSIONS

In this paper we have proposed Cognitive Radio as an extension for future wireless ad hoc emergency networks based on IAN architecture. We have listed system, network, and protocol requirements and outlined specifications of such networks. We have also proposed a new Medium Access Control algorithm that is built on top of Cognitive Radio.

The simulations of our CR MAC are ongoing. In the future we plan to extend our CR MAC with QoS capabilities (requirement T1). We also need to measure the impact of users' mobility (Requirement T3) and localizing capabilities (Requirement C4) on the overall performance of our algorithm.

We strongly believe that Cognitive Radio is going to bring a fresh air into the design of emergency networks.

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