

Dynamic Spectrum Access: An Emergency Network Case Study

Przemysław Pawełczak, Fokke Hoeksema, R. V. Prasad, and Ramin Hekmat

Abstract

One of the new approaches in radio frequency management called Dynamic Spectrum Access (DSA) promises to alleviate the problem of non-uniform spectrum usage. While some frequency bands are excessively utilized others are rarely used. A classical example where an issue of spectrum shortage is clearly visible are wireless emergency networks. In this article we discuss the challenges in implementing DSA in the context of future emergency networks and, accordingly, propose a novel architecture for these networks utilizing DSA.

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I. INTRODUCTION

Looking at national frequency plans of various countries, one might notice that they leave minimal or no space for the assignment of new wireless communication systems (see for example [1]). Yet recent measurements have shown that vast number of spectrum bands are rarely or seldom occupied by services assigned to them [2]. For example, the analog TV bands 14-20 (470-512 MHz) in the USA have a utilization factor ranging from 0.21 to 0.5 [3]. Thus, to keep abreast with the growing demand for bandwidth, many academic and standardization institutions are considering the concept of Dynamic Spectrum Access (DSA) independently, as a promising candidate for future radio access. Radios employing DSA can use parts of the radio frequency spectrum, for which they do not have proprietary rights, under the condition of causing no additional interference to Licensed User (LU) of that frequency band. Apart from minimizing interference, a DSA device may be constrained by the radio regulator with policies, e.g., which LU channels can be chosen with prescription of acceptable interference level.

This article aspires to discuss how DSA can be implemented in Next Generation Emergency Networks (*xGEN*), where the problem of scarce radio resources is significant¹. A recent incident to cite is the disaster in Enschede, the Netherlands, in May 2000, where a fireworks depot exploded and destroyed a large part of the city, killing 23 people and injuring more than a thousand. In the initial hectic hours after the chain of large explosions, fire brigade, police and relief workers of the medical team experienced a great deal of communication breakdown, both internally and with each another. The two main factors that caused difficulty in coordinating the teams were (a) lack of common standards for each disaster relief group and, (b) overloaded emergency frequency bands. In spite of the Netherlands having a common radio communication platform for all emergency services based on the TETRA standard, the above observation is a striking reminder that one can do better.

The natural solution to these problems is to utilize a Software Defined Radio platform for personal devices of emergency workers for inter-system communications, and DSA for seamless radio access

¹For an excellent overview of new concepts for these systems the reader is referred to [4]. Other interesting information on *xGEN* can be found on web pages of PSWAC and SAFECOM community, or MESA, WIDENS, and SPEARS projects.

within the emergency network. In this paper we explore a DSA system for emergency situations by proposing a simple implementation for an xGEN named Adaptive Ad-Hoc Freeband (AAF).

The article is structured as follows. Section II focuses on new concepts in spectrum regulation. Section III deals with implementational issues of a DSA for an xGEN. Section IV discusses the issues of finding the statistical properties of LU duty cycles and optimal decision for channel assignment in xGEN. Finally Section V concludes the paper.

II. DYNAMIC SPECTRUM ACCESS

The core feature of Cognitive Radio (CR) (so as Adaptive, Smart, Intelligent and Reconfigurable Radios [5]), apart from Artificial Intelligence features based on reasoning, is to increase the frequency agility using DSA. This feature was motivated by the growing need for bandwidth and lack of space in the frequency charts to accept new services. The idea of a somewhat intelligent selection of frequency bands came in parallel with the observation that a handful of radio systems do not use their assigned frequencies *at all*.

In DSA, access to new radio resources is purely dynamic and ad hoc in nature. Specifically, radio access to the bands which DSA systems have no legal rights, can be performed under the condition of causing no or minimal interference to the actual owners (Licensed Users) of the particular bands. The interference caused by DSA should not affect the QoS guaranteed for the LU. Radio access based on the state of the LU *only* is called Opportunistic Spectrum Access (OSA).

OSA is completely independent from radio regulators, who fully control the privileges to the specific parts of the radio band. The access to LU bands can be done using (1) the transmit power control, i.e. spread spectrum or ultrawideband techniques, or (2) the *Listen Before Talk* principle when the OSA can access LU bands only when it decides that the channel is not used. In OSA, spectrum can be accessed even if the spectral opportunity (the period during which LU radio band is considered by the OSA as free) lasts only for few minutes. In DSA access to a particular frequency channel is based on a set of various policies and state of the network exploiting DSA, including DSA device itself (battery level, QoS demands), apart from QoS levels perceived by LU in case of OSA.

Although for communication in DSA there is no need for external spectrum regulator, it is mandatory to have a basis for DSA systems to harvest particular radio bands. Unfortunately until now there are no regulatory policies for DSA systems. The concept of interference temperature proposed by the FCC can be treated as a basis for further studies on policies for DSA. The problem is complicated due to physical phenomena involved in radio transmission. For example in [6] we find definitions for conceivable,

observable, extendable, harmful, widespread, in-band, out-band, co-channel adjacent band edge, and far out of band interference. The types of interference to be considered as the basis for DSA policies are thus a matter of debate. In the following sections we will assume the most general case, i.e., each frequency can be used by DSA systems so long as its operation is purely transparent to LU.

We also note that on the regulatory level there is a growing need for increasing the flexibility in spectrum assignment and management. There are already *Spectrum Trades* (in United Kingdom or New Zealand) where owners of the frequencies (government radio regulators) sell their rights to third parties. Other concepts of modern regulatory based spectrum management include *Spectrum Leasing* (where spectrum is leased by the owner to other parties based on policies), *Spectrum Auctioning* (with more flexible selling process of frequency bands), *Spectrum Pooling* (where two or more parties decide on what basis they use the pool of frequencies), or *Negotiated Spectrum Use*. With a pool of new terms related to the next generation frequency access many are often used wrongly, or describe concepts differently, in the research and regulatory communities. For clarifications, further discussions on definitions and differences between novel radio spectrum access concepts we refer to [5].

Let us now introduce the concepts related to implementation of a DSA network in emergency situations. In the following section we describe the context of the DSA implementation, e.g., functional architecture, node architecture and the proposed solutions for DSA in xGEN.

III. XGEN SYSTEM ARCHITECTURE

A. xGEN Functional Architecture

Emergency communication networks are divided into different clusters, each of them managed separately (clusters of fire fighters, police, rescue services, etc.) and created on an ad hoc basis. During the operation each cluster will cooperate in helping other clusters to achieve their specific tasks. Such a cluster is called an *Incident Area Network (IAN)* [7] and it consists of two types of nodes. The first type is the *personal node*, carried by emergency personnel, with limited energy and computational capabilities and limited set of radio interfaces. The second type is the *vehicular node* capable of performing more computational tasks without any power constraints. However, the number of vehicular nodes is much smaller than the number of personal nodes. Structuring xGEN into IAN clusters has advantages for communication: it allows for efficient data aggregation, shorter transmission ranges, and efficient intra-IAN synchronization. At the MAC layer it allows for less contention and collision, and at the network layer only a few nodes are involved in routing.

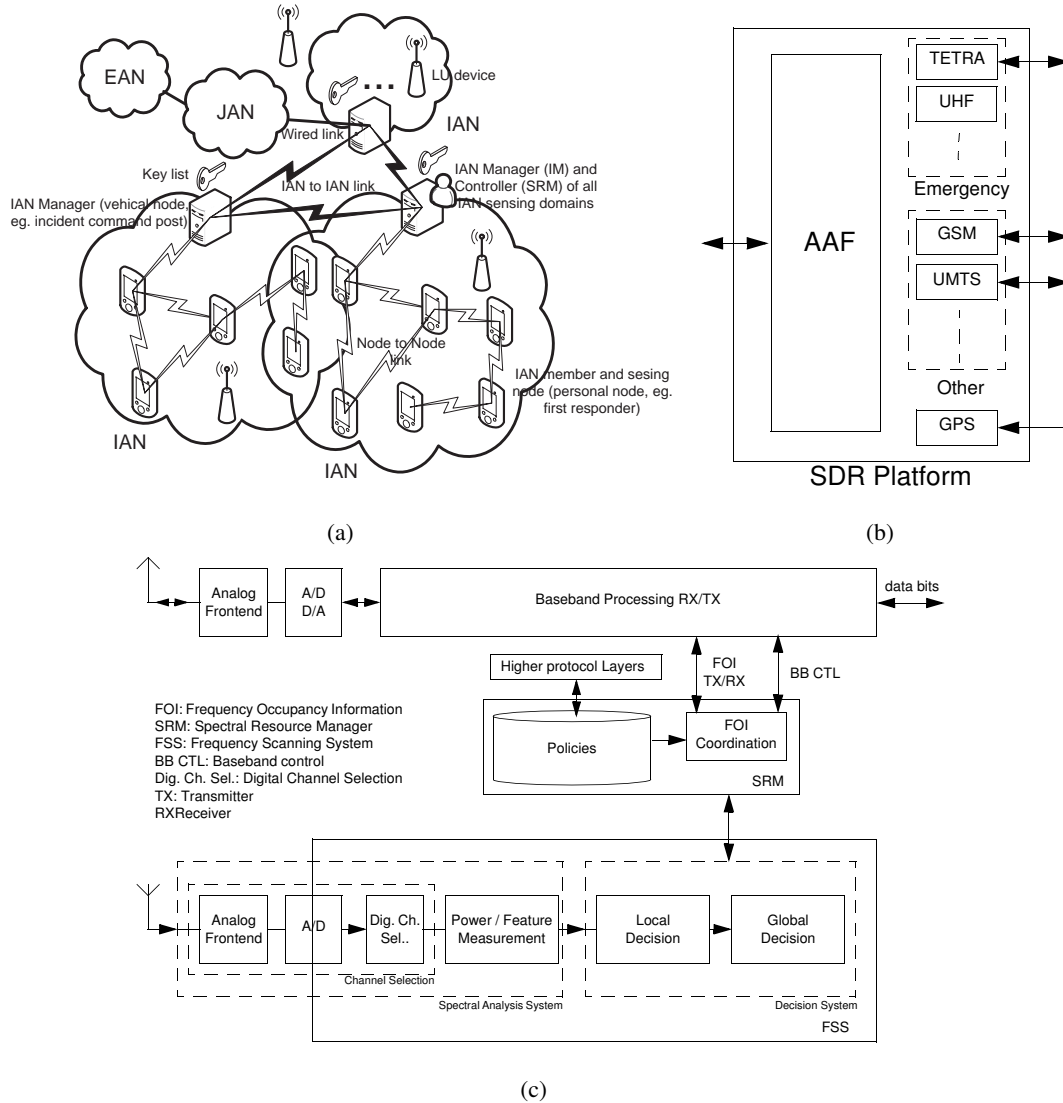


Fig. 1. (a) Functional architecture of OSAN; (b) SDR-stacks of generic xGEN node; (c) Radio system functions of the AAF architecture.

One of the IANs will have an interface to the *Jurisdiction Area Network* (JAN), exercising operational command over the set of all IANs. Moreover the JAN is connected to the *External Area Network* (EAN) such as Internet. The JAN is the infrastructure-based communication network for first responders in emergency services. It handles any IAN traffic that needs access to the EAN. Communication between different IANs typically routed through the JAN, while communication between an IAN and the JAN may use various radio technologies, e.g., satellite communication or GSM/UMTS. xGEN's functional architecture is shown in Fig. 1(a).

B. *xGEN: The Generic Node Architecture*

As we noted earlier, xGEN has to support the access to different radio technologies, since IAN consists of heterogeneous nodes. A natural approach is to map this requirement onto a Software Defined Radio (SDR) platform, where each generic xGEN node has the ability to reconfigure radio access hardware depending on the requirements set by the JAN. Software for different Radio Access Technologies (RAT) will reside in the node memory – like software for TETRA, analog UHF or public cellular networks, see Fig. 1(b). Because of the demand for fast setup-times, one cannot wait until nodes acquire software for a new RAT through over-the-air download. Even otherwise, the reconfiguration process has to be fast enough so the end users do not notice the delay in reconfiguration. The open question is how to properly design such a fast reconfigurable SDR hardware, since SDR files can be huge, and their recompilation and verification process takes time. A possible scheme for power-efficient and heterogeneous reconfigurable platform is described in [8].

A generic node contains additional network protocol stack, AAF, in its SDR memory, specifically designed for xGEN and exploiting DSA principles. Protocol design and implementation for AAF is constrained by the low power capabilities of personal nodes. Also rescue workers need a localization system in order to gain information regarding the rescue scene. For this, the legacy SDR stack of (D)GPS can be used in outdoor situations. For indoor operation extra localizing mechanisms are necessary.

C. *The AAF Radio System*

Due to the fact that in rural areas nodes of a IAN have to communicate over a distance of 500 m with a data rate of 2 Mb/s in single hop, the natural choice of frequency range for DSA in xGEN is the lower UHF. This conclusion is counterbalanced by the antenna size necessary for these frequencies. With a minimum bandwidth of 1 MHz and an SNR of 15 dB the AWGN capacity of a single channel is approximately 5 Mb/s. The modulation scheme chosen is OFDM as one would like to pursue the simple idea of loading and un-loading carriers as a means for avoiding interference with LU [9] (radio parameters of AAF xGEN are summarized in Table I [10]).

The radio system of a node consists of a baseband signal processing system (receiving and transmitting) and a Spectrum Scanning System (SSS) (see Fig. 1(c)). The latter consists of Frequency Scanning System (FSS) and a Spectral Resource Manager (SRM). While the FSS is responsible for distributed detection and signal-processing, the SRM function hosts the controlling entity. SRM uses policies, localization information and past experience to decide which frequencies to scan and how to use the scanning

Parameter	Value
Modulation scheme	OFDM
f_{min}	400 MHz
f_{max}	1000 MHz
Transmit power	30 dBm
Minimum channel SNR	15 dB
Minimum channel bandwidth	1 MHz
Maximum Doppler shift	278 Hz (150 km/h)

TABLE I

AAF XGEN RADIO SYSTEM PARAMETERS.

information. Each generic node contains an SRM, while only one node will make a decision for all the nodes at an instant (the issues related to distributed decision system are provided in Section III-C.2).

The baseband TX/RX and FSS functions operate on digital signals. The analog front-end is used for channel selection and downconversion/upconversion of analog signals (FSS has to be treated as purely digital, DSP based, system and therefore in Fig. 1(c) A/D converter is placed in between FSS and Spectral Analysis System). The front-end of the baseband processing system and the FSS may not have always the same capabilities, i.e., for spectrum measurements we take logarithm of signal power while for (de-)modulation purposes we consider *entire* signal shape. For the A/D and D/A conversion quadrature conversion systems are envisaged. It was observed in [8], [10] that if strong LU signals are allowed on a channel only a small channel bandwidth of 1-10 MHz can be supported by the OSAN. Higher channel bandwidth leads to higher power consumption by the A/D converters in the personal node (see Fig. 2).

It is envisaged that both baseband-RX/TX and the scanning systems have separate antennas (see also Fig. 1(c)). We believe that this can be used fruitfully for decoupling the baseband RX/TX communication and the SSS, as scanning can take place during the scan period in a Time Division Duplex fashion using a different carrier frequency than the one used for communication.

The SSS can follow many ways of detecting the LU. In the case, when the xGEN knows radio properties of the LU signal to be detected, or where the interaction between xGEN and the LU is allowed (by means of some form of spectrum etiquette) one can resort to feature establishment – identifying well known signal features of the LU signal, like carrier waveforms or pilot tones. For instance, in broadcast situations when the LU wants to be heard, it is expected that, especially in bad SNR conditions, feature establishment may outperform energy detection [11]. When xGEN wants to distinguish an LU from its own device, then an xGEN node could transmit a signature waveform that can be detected as a feature by another

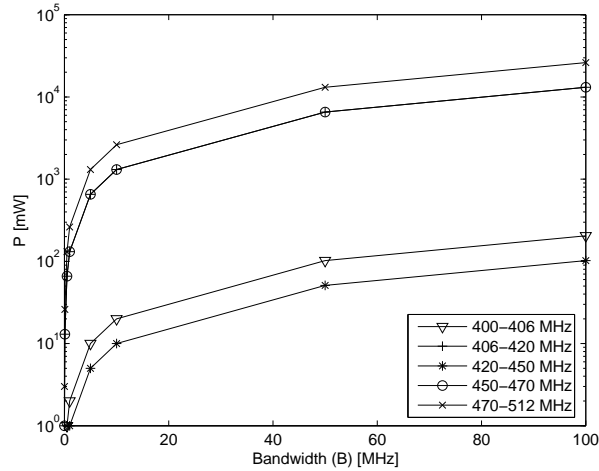


Fig. 2. Power consumption of an A/D converter as a function of bandwidth with dynamic range estimates assuming 2 pJ conversion step and sampling frequency $f_s=2B$ [10].

DSA-capable xGEN node. It is not obvious that energy detection alone is enough to achieve this.

A single scanning node may decide whether the LU frequency under consideration is free, hence it takes the local (hard) decision. The *Quality of Detection* (QoD) accounting for detection probability and false acceptance rate may be hampered by two phenomena. (a) *Multipath fading*, where the signals from the LU that travel different paths may or may not add coherently at the receiver. As a result, small changes in location relative to the wavelength of LU impact the QoD of SSS. (b) *Shadowing*, where an individual sensing node may be blocked by an obstacle, therefore may not be able to see the LU [5], [12]. To overcome these problems, *collaborative scanning* within xGEN is proposed. In this case, Frequency Occupancy Information (FOI) is gathered by a set of individual scanning nodes from all IANs of an xGEN, and disseminated to the decision entities participating in the xGEN using a special signalling channel and a protocol. In the remaining sections we will focus on these two aspects.

1) *The Common Control Channel (CCC) in xGEN*: It is a channel within *any* DSA network used as a medium to exchange data related to spectrum occupancy between nodes. As we discussed earlier, collaborative sensing is essential for the proper detection of the LU. In an xGEN the CCC can also be used for other purposes, such as transport of connection set-up messages, control data for network-bootstrap and node recognition (this type of channel is available in Bluetooth).

There are specific requirements for the CCC in xGEN. First, it has to be always available, i.e. it should cope with varying link qualities and be resistant to jamming. Second, its capacity should be properly

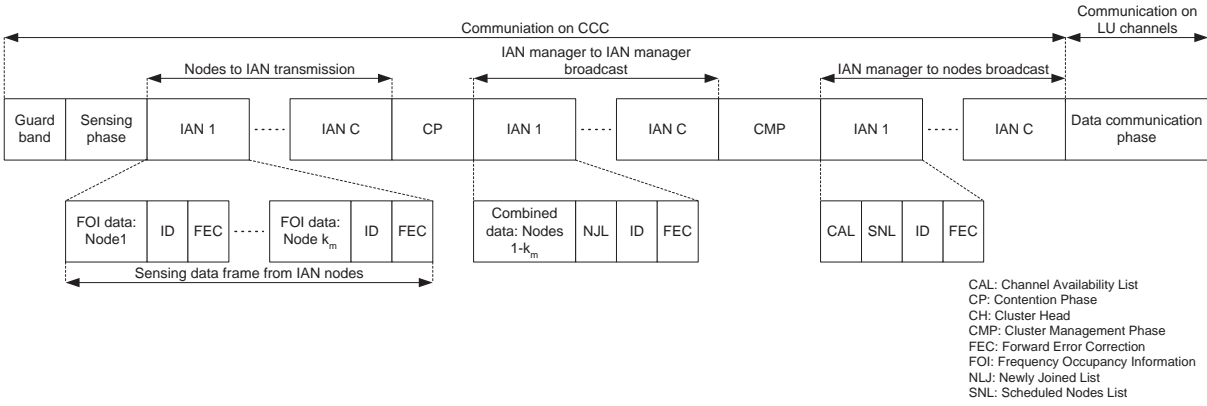
dimensioned i.e., bandwidth, SNR, data rate, cooperation with xGEN MAC protocol, error rate and delay need to be established before designing the CCC.

We can distinguish between two types of signalling for CCC. In *in-band signalling*, FOI can be transported within any unoccupied LU channel. However in-band signalling has a drawback which relates to the problem of connectivity. Consider the situation in which after being sensed the LU changes its state. Then xGEN has to coordinate on which channel exchange future FOI, which makes signalling rather complicated. For resolving this problem one could think of a TDD or frequency-hopping protocol in which at the end of each hop-interval not only a list of free channels – valid for the next interval – is exchanged between xGEN nodes, but also an identifier of the control channel for that interval (e.g. LO frequency and OFDM carrier number). System breakdown occurs when *no* empty LU channels are available, thus such a situation is not acceptable in emergency context.

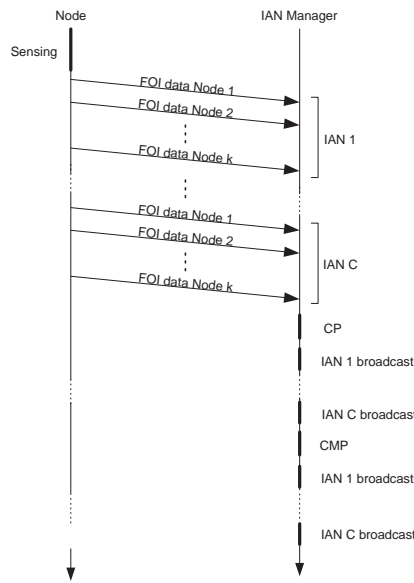
In *out-band signalling*, the DSA network has a dedicated control channel on which all spectrum sensing data is exchanged between nodes. Therefore, it allows xGEN nodes to always have a communication channel. For this case one may want to resort to ISM, military or TETRA bands. However this results in non-DSA assisted DSA networking, which is not recommended for an xGEN. Moreover, some of these channels are rather narrow (e.g. in the Netherlands there is a 1.74 MHz wide ISM band at approximately 433 MHz) which can easily be jammed. A simple solution would be to use pulsed UWB as a radio technique for the CCC. Assuming a BER threshold of 10^{-6} , and an outage probability less than 10%, for the fifth derivative of the Gaussian UWB pulse, with power limited by the FCC mask (7.5 GHz-10.6 GHz), a transmission distance of 700 meters can be obtained for 20 kbps with 64-PPM modulation. This is sufficient for system bootstrap and node identification, and also for FOI dissemination depending on the required data rate.

2) *Structure of the SRM Protocol for Cooperative LU Detection:* For the reasons discussed above, our AAF implementation of DSA for xGEN [13] will cooperatively detect the absence of LUs in a set of M radio channels. Our SRM protocol aims at network-wide knowledge of LU activity on each of M channels, thus there is no negotiation phase between IANs as to which channels are free, nor forcing nodes to change their decision in spectrum occupancy (in contrary to approaches proposed i.e. in [3], that opt for giving high priority to local decision of FSS).

Since almost all xGEN nodes have limited power capabilities, the SRM protocol has to assign sensing cycles such that it will not force one subset of all IAN nodes to scan excessively long. Thus in each sensing phase, a *different* subset of xGEN nodes will search for spectral opportunities. After the scanning period, nodes communicate with one of the dedicated nodes in an IAN to inform about the FOI pertaining



(a)



(b)

Fig. 3. (a) Frame structure of the proposed spectrum data exchange protocol; (b) Time flow diagram of the protocol.

to each LU channel. In the following phase all IANs exchange their FOI, thus all IANs can make the same decision about the presence of the LU and finally respond back to the xGEN nodes about channel availability.

Our xGEN architecture is (frame) synchronized, such that not only sensing, but all communication between nodes is based on TDMA. Data exchange of sensed data is done in the following phases. First a *guard band* is allowed for clock synchronization between xGEN nodes. This period of alleviating synchronization mismatch is due to the time uncertainty of each xGEN node. In the *Nodes-to-IAN-*

Transmission Phase the nodes selected by each IAN Manager (IM) in the previous frame, sense the set of frequencies for a specified period. After observation, each node has a reserved slot, to report its FOI to the IM. We note that transmission takes place in slots to minimize the probability of losing the data due to collision. One IAN reports one at a time, such that when nodes report to their IAN, all other nodes within other IANs remain silent, waiting for their turn in the frame. To protect the transmission each measurement is secured by a Forward Error Correction (FEC) scheme.

The Nodes-to-IAN-Transmission phase is followed by a *Contention Phase*, during which nodes moving from one IAN to the other register to a new cluster. A node decides to join a particular cluster based on the signal strength received from neighboring nodes. Analysis of the gathered FOI can be done by each IM in this phase itself and during CP, thus we do not need to reserve additional slot for processing in the frame.

In the next phase of the protocol called *IM-to-IM Broadcast Phase*, IMs send aggregated FOI to other IMs. We assume that all IMs are within a one hop reach from each other unlike other xGEN nodes in IAN with sensing capability (they can only reach the IAN with the best received signal strength).

Finally, in the *IM-to-Nodes Broadcast Phase* the results of the computation together with the Newly Joined List of nodes is broadcasted to other IANs. This part of the frame is also protected from errors by FEC. We note that, because each IM receives information from other IMs it can combine measurements applying the same criteria and thus result in the same Channel Availability List (CAL) at every IAN. Moreover using the newly joined list, each IM can update its node member list by removing all nodes that have been reported by other IANs.

We note that sometimes a cluster may have smaller number of nodes than required for achieving QoD. Therefore in the *Cluster Management Phase (CMP)* one of the IMs, called the *SRM Controller (SC)*, will decide how to divide slots for all IANs. Together with this information the SC assigns and then transmits the IDs of nodes that will transmit in the next sensing phase. Each node is chosen with equal probability. Additionally, the SC schedules randomly and broadcasts who is going to be the next SC for the next sensing phase.

While all IMs receive information from the SC, they transmit within the frame CAL and Scheduled Node List to their nodes. The transmission is secured by FEC. At the end of the sensing frame, data communication on the LU channels in CAL is performed. The complete frame of this protocol is depicted in Fig. 3(a) together with a protocol time flow chart in Fig. 3(b).

3) *Security of xGEN in DSA context*: The wireless network is vulnerable to attacks, jamming, spoofing etc., thus security plays an important role in the xGEN architecture, especially in SRM protocol context.

To avoid unauthorized or rogue nodes attacking the system, trust relationships are established between the entities in the xGEN while communication over the SRM protocol. An effective technique for building the trust relationship can be based on the key management principle [14], where it can safeguard against eavesdropping and man-in-the-middle attacks.

Keys are used to encrypt or sign the data exchanged between heterogeneous nodes within xGEN, for example to establish secure communication tunnels between sensing nodes and IM, and between IMs themselves. This avoids other rogue nodes listening to the channels as well as sending misleading data. For example, each node taking part in the sensing process has two keys stored in its memory at the time of deployment. Symmetric key encryption is used, thus the sensing node transmitting data to an IM assumes that the IM has the same key. Moreover sensing nodes do not generate keys and since the nodes have predefined keys stored in their memory, the key exchange between a IM and a node is limited. During the initialization of xGEN each IM will store keys for all the nodes and other IANs. Usually this key initialization is protected since all the nodes and the units carried by rescue personnel start after reporting to the JAN. Because the operation time of xGEN is relatively short, the need for key renewal procedure is limited. More information on the SRM protocol and its security can be found in [13].

Once the SRM finds the spectral opportunities, user communication in an xGEN can start. We will discuss this in the following section.

IV. DSA CHANNEL ACCESS FOR EMERGENCY SERVICES

Knowing which LU channels are free, xGEN can decide how to assign particular traffic flows to subgroups of each IAN. However the duty cycle distribution of the LU can affect the way the SRM protocol operates.

A. Analysis of Duty Cycle Distribution of LU

Usually, for DSA-analysis a model of the occupancy of LU channels is required and for the analytical studies is assumed to be exponential. We need to show that this distribution of LU duty cycle is one of the plausible candidates. Moreover, there are not enough studies on experimental measurements. The closest to provide such data is [3]. However authors do not explicitly state what kind of distribution each LU duty cycle has.

To find a plausible model we analyzed the measurements kindly provided by the Dutch Radio Regulatory Body [1], performed in 12 different cities of the Netherlands. On a single day the electric field strength of the frequency band 400-1000 MHz was measured once every 10 s using 100 kHz frequency

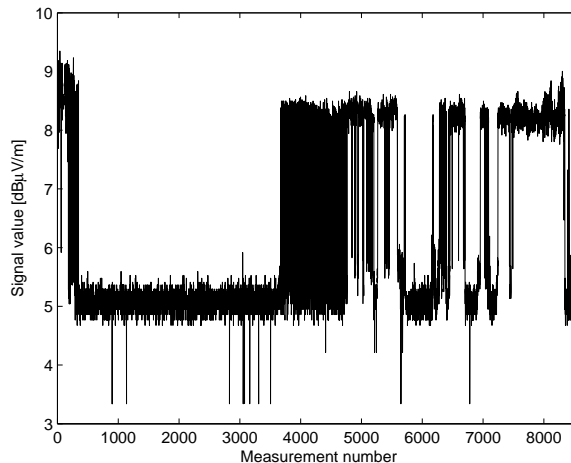


Fig. 4. An example of 24 hour measurement trace of LU activity for channel 445.6 MHz taken in city of Heerhugowaard, the Netherlands. Measurement parameters: antenna height 30 m; inter-measurement interval 10 s; channel size 100 kHz; estimated noise level $\nu_m = 6 \text{ dB}\mu\text{V/m}$.

bins. An example trace for the channel at 445.6 MHz (public trunking) is shown in Fig. 4. We see that there are some long on-off phases and some shorter transitions. Only on a few occasions the channel is continuously occupied or free.

Focusing on the case when the channel is experiencing rapid transitions, we observed that the behavior of the LU is best modeled as a two state markov process (Gilbert model). The transition probability from ‘on’ to ‘off’ state is 0.9. The probability for the transition from ‘off’ to ‘on’ state is 0.76. The measured mean time spent in the ‘on’ and ‘off’ states are 72 s and 245 s, respectively.

The observations above imply that (a) the assumption of an exponential distribution of LU duty cycles is valid (at least for data-like LU channels), and (b) for optimal utilization of spectral opportunities by xGEN, prediction of LU behavior can be inaccurate. This also implies that the maximum interval between two consecutive frames of the SRM protocol have to be specified by policy [12]. The reason behind this requirement follows from the *maximum length* of interference that xGEN can introduce.

B. Channel Allocation

Having the information obtained from the SSS, xGEN, through IMs in each IAN, can map the network demands in terms of traffic flows into available resources. Specifically, a set of $\mathbf{F} = \{f_1, \dots, f_K\}$ flows with respective rates $\mathbf{W} = \{w_1, \dots, w_K\}$ generated within each IANs can be mapped to onto M radio broadcast channels on specific frequency. Each channel has a data rate of $\Phi_j = B_j \Lambda_j Q_j$ b/s, where B_j is

the channel j bandwidth, $\Lambda_j = \frac{\lambda_j}{\sum_{j=1}^M \lambda_j}$ is the normalized arrival rate of LU on channel j , and $Q_j \in [0, 1)$ is the instantaneous QoD of channel j performed by SSS of xGEN. IMs in each IAN decide which assignment of flow f_i to channel j gives the best performance (profit) p_{ij} , i.e., the improvement in the quality of the rescue-operation's communication, by assigning flow f_i to channel j . The spectrum usage need to be maximized across the channels using the following Integer Programming (IP) formulation

$$\max \sum_{i=1}^K \sum_{j=1}^M x_{ij} p_{ij}, \quad x_{ij} \in \{0, 1\},$$

such that

$$\sum_{i=1}^K x_{ij} w_{ij} \leq \Phi_j, \forall j \in \{1, \dots, M\},$$

where w_{ij} is a fraction of flow f_i placed in channel j .

This is one of the variants of classical resource allocation problem, which is NP-complete. Finding a solution to the assignment which accommodates all flows is NP-hard [15]. This type of optimization should be performed in every sensing interval by IM. Further, to compute near optimal assignment usually, some heuristics algorithms are employed.

Now, to get some insights into the performance of the system we will discuss the issues related to the channel assignment considering only LU activity on the channels. It is in fact important to see, in general, whether we can get any reasonable data rate as well as how efficient the part of the spectrum not occupied by the LU can be used – indeed without using the complicated dynamic programming or IP solution for the above optimization problem.

We can propose simple assignment scheme, *Least-used with Channel Hopping* (LeUCH), when IM in IAN chooses a channel m with $\lambda_m = \min(\lambda_1, \dots, \lambda_M)$ for a new flow, and whenever IM finds out that LU wants to use the channel, it then tries to choose another channel with the smallest λ_m possible and continue transmitting rest of the data there.

For comparison we can enlist two other schemes of assigning the traffic flows on LU channels [12].

- 1) IM in IAN chooses a channel randomly. We call this assignment scheme as *Random* (RnD).
- 2) *Least-used* (LeU), when IM in IAN chooses for new flow channel m with $\lambda_m = \min(\lambda_1, \dots, \lambda_M)$, and does not try to reassign the flow when LU became active on the channel.

In RnD, LeU and LeUCH flow is considered blocked with the arrival of LU, e.g., type II blocking occurs [12]. Type I blocking occurs when channel is being occupied by DSA network itself.

Results of the simulations for the total probability of blocking (type I and II blocking) with different access schemes are shown in Fig. 5(a). A simulation scenario was constructed such that it closely

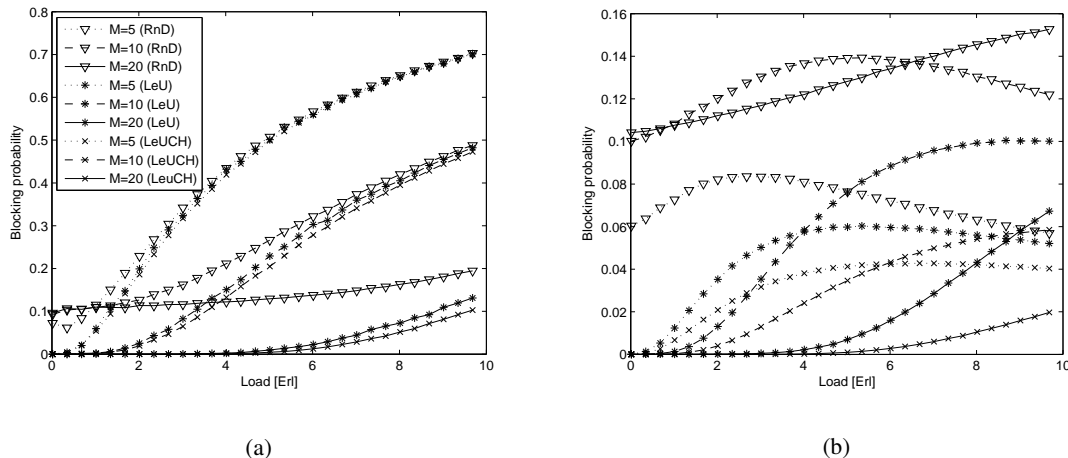


Fig. 5. (a) Simulation of blocking probability for $M=\{5,10,20\}$ for different channel access schemes. Channels are utilized non-uniformly by LUs, i.e., for $m = 1, \dots, M/2$ $\lambda_1 = 20$, $\lambda_m = \lambda_{m-1} - \lambda_1/2$ and $\mu_M = 3$. Rest of the channels are considered unoccupied by LUs. (b) Simulation of type II blocking probability for same xGEN environment.

mimicked the operation of an xGEN, i.e., comprising of LU channels with non-uniform utilization with a set of free non-LU channels. For three different sets of frequencies we obviously see that the LeUCH scheme outperforms others. What is interesting to see however is that for the moderate number of channels the difference in blocking probability between LeU and LeUCH is rather small (less than 0.01). The difference between LeU and LeUCH is more visible in the case of $M = 20$ channels and it is due to the fact that the secondary packets have more opportunities to switch to different channels.

In Fig. 5(b) a plot for the type II blocking probability is shown. For $M = 5$ difference in type II blocking is small for a moderate load from xGEN. But for $M = 20$ this difference is quite significant (around 0.2). However while LeUCH is the most efficient scheme compared to other two, the difference in terms of blocking probability between LeU and LeUCH in many situations is negligible. It is easy to see that LeUCH increases signalling traffic on the CCC since xGEN must schedule the hopping.

All simulations were done assuming perfect LU detection. However total blocking probability in the presence of detection errors of SRM can of course diminish the throughput. We emphasize here that the blocking probability can directly imply the spectrum gain for the xGEN, i.e., if the probability of blocking is small then the spectrum utilization is high.

V. CONCLUSIONS

In this article we presented the DSA principles from the implementation point of view. We proposed xGEN, the Next Generation Emergency Network, where there is an acute spectrum scarcity. We brought in

the concept of SDR and DSA into the xGEN, called AAF. We outlined the real challenges in implementing such networks. We have designed a protocol, for managing DSA within xGEN. Apart from this we have also presented a study of actual measurements and a possible model for the occupancy of LU. We have shown the avenues for sharing the free spectrum through simulation studies. Thus we have produced a complete architecture for xGEN which can take care of the non-availability of dedicated bandwidth and can maximize throughput as well. We feel that this is the first step in the right direction.

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