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Review Article

COGNITIVE COMMUNICATION SYSTEMS FOR PUBLIC SAFETY

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Wireless communications bring valuable opportunities for coordination of crisis management during extreme occasions of public safety and security related events. However, there are some tough challenges for providing an effective wireless communication infrastructure during these occasions. In this paper, firstly public safety and security related events will be described in detail and specific wireless communication requirements will be given. Then the solutions and requirements to overcome the challenges will be discussed. Finally, role of cognitive radio as a solution application to the communication phenomena in these extreme situations will be described.

Keywords: Wireless communications, Public safety, Cognitive radio

INTRODUCTION

The introduction of cellular systems and evolution of analog wireless communications systems to digital systems opened an era of hundreds of millions of wireless communications users around the globe. Cellular phones are used in the first place in case of extreme situations or emergency cases and rescue-safety operations can benefit from prevalence of cellular wireless technologies during and just after extreme situations like hurricanes, earthquakes and collapse of buildings or mines. However, events around the world such as unfortunate attacks of 9/11, hurricane Katrina, Indonesian tsunami, and devastating Pakistan floods revealed problems about legacy wireless communications systems from a different aspect: Wireless communications of all kinds cease to work in extreme situations because of the damaged infrastructure, congestion caused by overwhelming request for communicating and abnormal communication parameters, e.g., drastic changes in air interface because of weather conditions during natural disasters. Establishing communications under severe conditions of extreme situations to detect and locate survivor communications or to maintain reliable communications between the first responders of various public safety organizations require reconfigurable and intelligent communications techniques. For instance, the radio should sense the operational environment of communication and

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autonomously adjust its parameters accordingly to execute these tasks.

Another important issue is interoperability of public safety organizations or first responders. Wireless communications infrastructure may not satisfy the requirements of large operations that are needed during the spread natural disasters and events because, the number of the first responders increases with increasing population but, allocated resources and technology does not change by the time. Hence, it becomes nearly impossible to communicate even for the first responders of the same organization because of insufficient resources such as frequency spectrum. Besides, if there is no common infrastructure or technology defined to cover all public safety organizations in one region, it becomes nearly impossible to coordinate first responders which finally leads to inefficient resource usage and loss of crucial time in the very first response phases of the events.

Cognitive radio is an emerging wireless technology which can introduce methods for efficient, secure, and reliable communications between different public safety units during extreme situations. Adaptability and sensing features of cognitive radios present solutions to the problems mentioned e.g., opportunistic spectrum usage and interoperability. Moreover, user localization techniques can be explored to estimate the victims and first responder's locations. The signals from the devices of the victims who are trying to reach out can be detected; their signal types can be identified by using spectrum sensing methods. Furthermore, first responders' wireless communications devices can communicate with the victims' devices even though original core telecommunications network may be down by benefiting from the adaptation feature of cognitive radio systems or the location of the victims can be estimated extracting required information from the received signals.

BACKGROUND AND CURRENT STATE OF THE ART

One of the best cases related to the complexity of the issues of public safety communications is the United States public safety communications system. There are more than 74.000 public safety organizations using various wireless communications technologies and frequency bands in the United States according to National Public Safety Telecommunications Council (NPSTC). The interoperability issues of these organizations is a well-known problem: first, effective communications among the first responders, i.e., police and fire departments during the emergency; second, cooperative communications that can enable these public safety organizations from different disciplines to make jurisdictions to work together in emergency preparedness and response. Even though the frequency spectrum allocation and licensing policy of Federal Communications Commission (FCC) since 1930's (Jesuale, 2007) seems to be the source of problems in the first place, the vertiginous evolution of wireless communications technologies should be also indicated as another reason for this divided map of organizations. There are some efforts to solve these issues which can be categorized in two paths: (i) Regulatory issues; (ii) Technological challenges.

Traditional communication system design is based on allocating fixed amounts of resources to the user. Adaptive design methodologies, on the other hand, typically identify the requirements of the user, and then allocate just enough resources, thus enabling more efficient utilization of system resources and consequently increasing capacity. Even though there have been studies and definitions on radio systems which are computationally intelligent to choose and support multiple variations of wireless communications systems (.MitolaIII, 1999; ArslanandJ MitolaIII, 2007; Cabric *et al.,* 2004; Fettweis *et al.,* 1996; Bronzel *et al.,* 1997) a widely accepted terminology is introduced by Joseph Mitola III through Software Defined Radios (SDR) (Joseph, 1993) and later on cognitive radios. The term Cognitive Radio is defined by Joseph Mitola III in his Ph.D. dissertation called: "Cognitive Radio: An Integrated Agent Architecture for Software Defined Radio" (Joseph, 2000) as:

"The term cognitive radio identifies the point in which wireless Personal Digital Assistants (PDA) and the related networks are sufficiently computationally intelligent about radio resources and related computer- to-computer communications to:

1. Detect user communications needs as a function of use context, and
2. Provide radio resources and wireless services most appropriate to those needs.

Cognitive radio has been perceived as an extension of software defined radios earlier but later in Federal Communication (2003) FCC suggested that Cognitive Radio (CR) also should include enhancements on spectrum awareness: "A CR is a radio that can change its transmitter parameters based on interaction with the environment in which it operates. The majority of cognitive radios will probably be Software Defined Radios (SDR), but neither having software nor being field programmable are requirements of a cognitive radio."

Some of the communications systems such as the ones in the cellular bands and ISM bands have dynamic usage patterns which do not use the allocated frequency spectrum continuously in time and space as static users like TV emitters and radio wave transmitters. This fact may lead to opportunistic spectrum usage by communication devices with spectrum sensing capability. Deployment of cognitive radios as secondary users in these bands is also another aspect of achieving spectral efficiency (Krenik and Batra, 2005; Brodersen *et al.*, 2004; Marcus, 2005). Moreover, currently some companies are working on implementation of cognitive radios that will work on TV broadcasting bands. There are also some challenges and limits investigated at the physical layer level of the communications stack. These challenges can be listed as geographical limits, issues related to signal detection, noise and quantization uncertainty (Sahai, 2004; Haiyun, 2005) listed three key aspects of Cognitive Radio discussing some physical layer limitations and applications of wide band cognitive radio systems:

- Sensing - A cognitive radio must be able to identify the unused spectrum segments;
- Flexible - A cognitive radio must be able to change signal frequency and spectrum shape to fit into the unused spectrum segments; and
- Non-interfering - A cognitive radio must not cause harmful interference to the primary users.

COGNITIVE RADIO FOR PUBLIC SAFETY

The advantages of CR technology over legacy systems stems from the introduction of flexible, re-configurable and re-programmable wireless communications systems. One of the major impacts of these systems is seen on interoperability issues on both military communication systems and public safety communications. However, there are some challenges from the aspect of public safety applications; especially on the security issues and convincing the regulatory bodies to allocate specific frequency bands for the realization of these wireless communications technologies for public safety communications (Baltimore, 2005; Scaperoth, 2006). In the light of these developments, National Public Safety Telecommunications Council (NPSTC) which is a federation of organizations whose mission is to improve public safety communications and interoperability, joined SDR Forum which is the supporting organization for SDR and CRs to come up with a solution to the interoperability problems of public safety agencies. NPSTC Software Defined Radio Working Group published the “Cognitive and Software Radio: A Public Safety Regulatory Perspective” report (John, 2004) in June 2004 employing cognitive radio as solution addressing FCC to solve the problems regarding allocation of frequency bands, testing and security. Unfortunately, one year later, the interoperability problems of public safety agencies became a major issue during the event of hurricane Katrina. Immediate action was taken by FCC by submitting a report to US Congress addressing the interoperability problems: as the first action, 700 MHz frequency band (108 MHz of spectrum from 698-806 MHz) is allocated to public safety and Congress directed that TV broadcasters should complete transition to digital broadcast technologies and vacate the spectrum in order to accommodate wireless commercial and public safety uses of the spectrum until February 17, 2009 (FCC). For long term, US Congress also indicated smart and cognitive radios as a first level commercial technology for the solution of interoperability issues of public safety communications systems that will operate in these new bands. Beside these activities, Homeland Security initiated SAFECOM; a communications program providing research, development, testing and evaluation, guidance, tools, and templates on interoperability of communications related issues to local, tribal, state, and federal emergency response agencies. SAFECOM published (US Department Homeland) detailing public safety communication device functional requirements which can be covered by cognitive radio technology. Moreover, SDR Forum also constituted public safety special interest group and published (SDRF, 2006) recommending SDR and cognitive radio technologies for SAFECOM requirement satisfaction and advanced spectrum allocation at 700 MHz frequency band public safety operations. Beside these activities, Jesuale (2007) discussed implementation of policy based cognitive radios for public safety and industrial Land Mobile Radio (LMR) bands currently in use.

It is also important to mention about the European and collaborative efforts for public safety communications interoperability since last two decades. Terrestrial Trunked Radio (TETRA) is a digital trunked mobile radio standard developed by the European Telecommunications Standards Institute (ETSI) (Jones, 2007; TETRA). The purpose of the TETRA standard is to meet the needs of traditional Professional Mobile Radio (PMR) user organizations such as public safety, transportation, government, commercial, military, etc. Deployed first in 1997 (Release I), TETRA uses Time Division Multiple Access (TDMA) and full duplex voice communications. Most importantly, it employs two different air interfaces, between the base station and radio terminals (1) and the Direct Mode Operation (DMO) interface (2) allows terminals to operate in local radio nets without support of main framework. Release II brought improvements on voice coders/decoders and also improved data rates up to 538 kbps for 150 kHz bandwidth and 64-QAM modulation. Several companies and research institutions also initiated EUROPCOM project which aims to investigate and demonstrate the use of Ultra Wide Band (UWB) radio technology in emergency situations to allow the precise location of personnel to be displayed in a control vehicle and simultaneously improve communications reliability (Emergency Ultra wide band Radio for Positioning and Communications). It is planned as an extension to previously deployed TETRA system to achieve traceability for first responders in extreme cases that can lead to loss of their lives. European Telecommunications Standards Institute (ETSI) and The Telecommunications Industry Association (TIA) agreed to co-operate for the constitution of mobile broadband specifications for public safety. The means for this activity have been provided in the form of a partnership project called MESA, originally known as the Public Safety Partnership Project (PSPP), which constitutes the legal and operational framework ensuring a swift progress of results. The aim of the project MESA is to produce globally applicable technical specifications for digital mobile broadband technology, focusing initially at the sectors of public safety and disaster response (Mobile Broad band for Public Safety Project"; Cognitive Radio Systems for First Responders; Hasan *et al.*, 2006).

Even though cognitive radio technology found one of its initial application as spectrum agile radio for public safety communications, diverse inherent features of cognitive radios introduce challenging research and implementation opportunities for public safety communications. System level requirements of public safety cognitive radio are detailed from the aspects of achieving awareness, learning and decision making in BinLe (2007) and Jesuale (2005) introduced employment of cognitive radio technologies depending on the primary (current public security agencies) and secondary (later joined commercial entities) user approach in current public safety frequency bands. Interoperability and efficient usage of the frequency bands are expected to be achieved by the deployment of new digital cognitive radio technologies both for primary and secondary users. Hoeksema (2005) and Pawelczak (2005) propose an adaptive ad-hoc cognitive radio emergency/disaster relief network. First the service and system requirements are defined on data messages, real-time voice, still picture, real-time video, and remote control. The proposed cognitive radio system is a spectrum agile radio diverted from IEEE 802.11 standard based on spectrum polling and Distributed Channel Assignment (DCA) concepts.

Media Access Control layer (MAC) design and algorithm implementation are also detailed. A reconfigurable hardware architecture for emergency networks, depending on Orthogonal Frequency-Division Multiplexing (OFDM) based cognitive radio is introduced in Qiwei (2006). This architecture is intended for wireless nodes which are expected to employ adaptive bit loading and power loading for spectrum sensing purposes. Hardware implementation of such cognitive radio architecture in a flexible and energy efficient way is studied benefiting from the heterogeneous and reconfigurable technologies of Field Programmable Gate Arrays (FPGAs), DSPs and Application Specific Integrated Circuits (ASICs). Besides, Green (2007), Wei (2007) has introduced a real-time cognitive radio test bed for interoperability and spectrum sensing experiments.

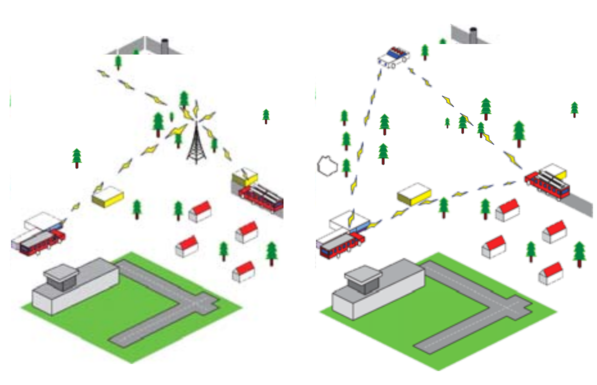
Physical Layer Configurability

Communication congestion originating from the nature of the extreme situations and interoperability problems stemming from resource insufficiency of communications systems are the two main factors that cause the cessation or inefficiency of public safety communications systems during extreme situations. The solution to these problems can be found by understanding the wireless channels and by developing the physical layer configurability. One of the widely studied features of the cognitive radios is their ability to sense the communications environment, especially the spectral occupancy. Cognitive radios are affliated with the public safety communications from the aspect of spectrum sensing and opportunistic spectrum usage, in general. However, cognitive radios can also autonomously observe and learn about the radio environment, generate plans, and even correct mistakes. These features give the cognitive radio technology the flexibility and adaptability to overcome the problems of public safety communications systems.

As the radio senses the operational environmental features such as frequency band occupancy, wireless channel characteristics like fading, time and frequency selectivity, delay and Doppler spread, subsequently, it can be aimed to achieve physical layer configurability through autonomous selection of appropriate algorithms for functional blocks of frequency, signal power level and waveform selection, modulation-demodulation methods, encoders-decoders, interleaving and de-interleaving, etc. Depending on the requirements of the operational environment cognitive radio should be able to select appropriate algorithms for each functional block to execute the required tasks successfully. This is called algorithm selection level adaptability (Gerard, 2006). For instance, interleaving and de-interleaving functional block can change interleaving method depending on the fading values or depending on the selectivity of the wireless channel.

Another aspect of physical layer configurability research is the introduction of an ad-hoc networking mode for public safety radios. Ad-hoc networking can be achieved through the implementation of a predefined common communication channel such as the un-addressed voice channels in TETRA or broadcast voice channels for talk groups of traditional public safety wireless communications systems

Figure 1: Adaptation of Communication Modes: CoreCommunications Mode vs. Ad-Hoc Mode



(a) (b)

(Hoeksema *et al.,* 2005; Pawelczak *et al.,* 2005; QiweiZhang, 2006). Moreover, the crucially important issue for victims and first responders is that the communications between first responders will not be ceased if the core communications network is down. The ad-hoc mode and core communications modes are depicted in Figure 1.

Security Considerations

The voice and data communications of public safety workers such as law enforcement officers and national authorities can be protected from being intercepted by individuals who are potential threats to public safety. There can be illicit organizations that can attempt interception of the signals of public safety organizations. Therefore, it is crucial that the over the air information of the all kinds of public safety organizations should be coded or encrypted. Any information flaw may result with intrusions, theft attempts and looting or may affect the performance of public safety missions. Cognitive radio must distinguish its actions and deploy appropriate security levels for each of them. As a consequence, cognitive radio must take into account the loss due to the encryption overload (Robert, 2001).

A critical requirement for an encrypted communications system is that it must be able to obtain an encryption update, i.e., to obtain a current encryption key to support secure communications with appropriate destinations and authorized users. Although when the device will be reprogrammed it is historically accomplished by transporting the device to a secure facility, ideally, the new encryption key should be able to obtain remotely by authorized subscribers because the user can be unable to go to a specific location for this operation. Therefore, over the air keying is an important system requirement that enables encryption update using the available radio channels, rather than physical transportation of the equipment (Summitek Co. Signal Intelligence Concept; Carlos *et al.,* 2006; "Software Communications Architecture (SCA)"; Lind and Littke, 2004).

Locating the Victims

One of the most effective ways of tracing victims in extreme cases and providing coordination between first responders is to track the wireless signals emitted by the devices in the environment. Recent developments in the wireless communication area have also impacts on emergency call systems such as enhanced 911 (E911) services. These systems are designed to provide improved service for victims especially with respect to instant delivery of the victim's location information to the local Public Safety Answering Point (PSAP) to which the caller is connected. Wireless E911 services have two phases; while the Phase I only asserts the identification of the caller ID and cell phone tower for location estimation, final stage of Phase II requires wireless service providers to provide even more precise location information, specifically, information accurate to the closest PSAP (Federal communication Commission, Wireless 911 Services). Wireless service providers employ techniques either based on radiolocation methods depending on wireless network or assisted techniques based on location services such as Global Positioning System (GPS) over mobile terminals. Network approach can apply triangulation techniques such as Angle of Arrival (AOA) and time difference of arrival (TDOA) or can be implemented using location signature by implementing fingerprinting methods (Drane, 1998). Even though the tracking capabilities are improved, network based location information systems and services developed on the requirements of E911 (or E112 in Europe) are insufficient from the aspects of:

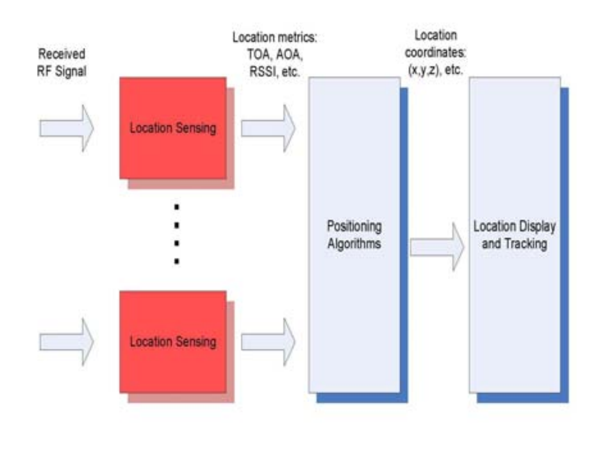
- Dependency on the network infrastructure which can be damaged during an extreme situation;
- Congestion due to the capacity limit of either network or PSAP, resulting latency or impossibility of providing victim's location information in timely manner;
- Some factor that are not directly related to the E911 system such as if the victim calls some other number for help instead of 911 and if the batteries of the victim's radio is low to make a call.

Even if the original core telecommunications network is down, search and rescue efforts can benefit from prevalence of cellular wireless systems during the extreme cases by communicating with the victims, or their locations can be estimated by extracting the required information from the received signal. Even though there had been some efforts to detect the location of the victims in disaster environments by employing UWB communications and TETRA system jointly, these approaches are limited to the range of a few meters due to the characteristics of the employed technology (Emergency Ultra wide band Radio for Positioning and Communications). However, awareness feature of cognitive radios can provide a comprehensive solution to the location sensing requirements of public safety communications in extreme cases. It should be aimed to investigate how to accomplish communication with the survivors and how the estimation of their location, utilizing received signals can be achieved (Gorcin, 2009). This specific aspect of awareness requires deployment of public safety radios which combine the channel models developed for extreme cases and physical layer configurability taking the security issues into the consideration. The ad-hoc networking concept can also contribute to the goal; distributed radios can behave like sensors for victim transmission detection and location sensing methods can also benefit from the distributed radios for location estimation.

Detecting and locating victims in a disaster area through their wireless devices and the nature of the mentioned problems above require research for intelligent, secure and robust communication techniques. In this aspect, even though cognitive radio technology is commonly related to public safety communications from the aspect of interoperability, the cognitive radio features of awareness, learning, and intelligence can be beneficial for victim and first responder location estimation. Awareness feature of CRs aims to provide useful information to wireless devices and networks for enabling them to interact and to learn from surrounding environment. Therefore, location based services of cognitive radio technology can be employed to detect and locate victims.

When the wireless communications systems are considered, location estimation research can be discussed in three folds: (i) channel modeling, (ii) location sensing, and (iii) positioning algorithms (Pahlaan, 2002). Channel modeling deals with estimation of channel parameters and assessment of the effects of these parameters over the proposed system model. Location sensing feature introduces methods to define and to compute the metrics for location estimation. On the other hand, positioning algorithms are employed to estimate the location coordinates for wireless devices taking the channel and location metrics into consideration. Proposed approach is also illustrated in Figure 2.

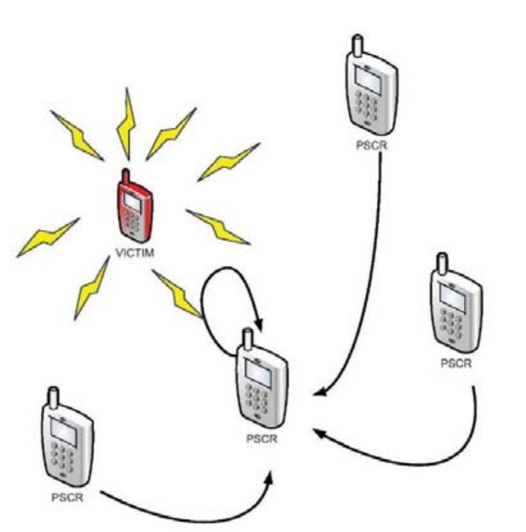
Figure 2: Location Estimation Processes Path



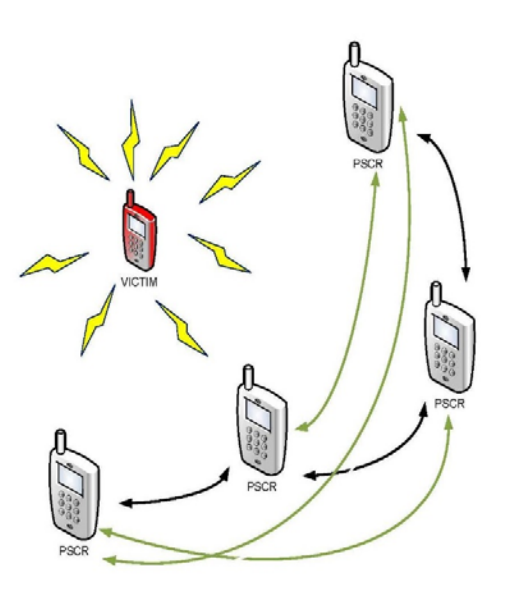
Radiosensing Methods: Radiosensing methods are antenna-based location sensing applications which can be categorized under three groups: range-based schemes, range-free schemes, and pattern matching- based schemes. In range-based schemes, a set of parameters are used to estimate the location information of the target device. These parameters can be TOA, RSSI, AOA, and TDOA for classical radiosensing methods. The statistical information acquired from the received signal are used to calculate these parameters. On the other hand, range-free schemes are simple sensing methods which provide a coarse location information. Hop-count-based approach (e.g. Ad hoc Positioning System (APS)), centroid, and area based approach are the three main approaches for range-free schemes. CRs can benefit from the range-free schemes especially over the wide spread operation areas such as wild forest fires and large scale floods for estimation of the location of the victims in a coarse way. A couple of these methods, such as APS and centroid can be combined adaptively for better estimation results. Pattern matching-based schemes are based on probabilistic models and they can be used to estimate the terminal locations when signal measurements are available. Various attributable variables can be used such as signal strength and power delay

Figure 3: Implementations of Positioning Techniques

(a) Centralized Positioning



(b) Decentralized Positioning



profiles and different probabilistic modeling approaches can be employed based on the type of the application. For instance, Bayesian and Hidden Markov models are frequently used for indoor location sensing applications. Hence, pattern matching-based schemes can be deployed by public safety cognitive radios for the cases such as fire rescue victim locating and short range tracking. Positioning techniques can also be classified into two categories depending on the choice of implementation: (i) decentralized (self)-positioning, (ii) centralized (remote)-positioning. These approaches are illustrated for public safety CRs from the aspect of victim tracking in Figure 3.

CONCLUSION

The advanced flexibility, configurability, learning and awareness features of cognitive radios itself forward to solve the current problems of public safety communications systems. Moreover, the assessment of communications requirements in extreme and emergency cases, taking the advancements that can be achieved by the employment of cognitive radio technologies into account, clearly indicates that it can be possible to achieve interoperability and non-ceased communications between the first responders in an efficient, reliable and secure way. Location and environment awareness features of cognitive radios can provide improvement at the quality of service of public safety communications with the aid of mobility management and statistical learning and tracking techniques. Communication and data storing security can be enhanced by the security and privacy methods of awareness feature of CRs.

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