Performance Improvements in Heterogeneous Wireless Networks for First Responders

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Abstract—Efficient communications are crucial for disaster response and recovery. However, most current public safety land mobile radio (LMR) networks only provide narrowband voice service with limited support of low-speed data services. In this paper, we study to enhance the interoperability of LMR with commercial wireless cellular networks, by which a wide variety of benefits can be offered to disaster responders, including new multimedia services, increased data rates and low cost devices. Our approach is based on Session Initial Protocol (SIP) and a joint radio resource management framework. In addition, an optimal radio resource management scheme is proposed to maximize the overall radio resource utilization and at the same time guarantee service availability and continuity quality of service (QoS) for disaster responders. The effectiveness of the proposed approach is illustrated by numerical examples.

I. INTRODUCTION

Disaster response and recovery require timely interaction and coordination of disaster responders in order to save lives and property. Efficient communications are crucial during disasters. With recent advances of wireless technologies, mobile wireless networks play an increasingly important role in disaster response. Currently, public safety land mobile radio (LMR) is used by public safety agencies for coordinating teams and providing rapid emergency response. Most public safety mobile wireless networks currently being deployed throughout the world are based on two digital narrowband LMR technologies: Association of Public Safety Communications Officers (APCO) Project 25, standardized by the Telecommunications Industry Association (TIA) and Electronic Industries Alliance (EIA), and Terrestrial Trunked Radio (TETRA), standardized by the European Telecommunications Standards Institute (ETSI). There are also some efforts for underway within TIA Technical Requirement Working Group 8.08 (TR8.08) and Project Mobility for Emergency and Safety Applications (MESA), a partnership between TIA and ETSI. Although some technologies (e.g., IEEE 802.11a/j in the 4.9 GHz band) are being considered as candidate access technologies for future public safety radio networks, most current deployed networks provide narrowband circuit-switched digital voice service with limited support of low-speed data services [1].

In contrast, current commercial wireless cellular networks can support packet-switched, broadband technologies with a variety of multimedia applications that include voice, data, web browsing and video [2]–[22]. The significant differences (in terms of services and data rates) between these two kinds of wireless networks are largely due to market forces, requirements, spectrum policy and other factors [23]. For example, the commercial wireless cellular user community is two orders of magnitude larger than the public safety LMR base. As a consequence, the R&D investments in commercial wireless cellular networks dwarf those made in public safety LMR networks.

During disasters, efficient communications are crucial for disaster responders in disaster response and recovery. For example, it is desirable for the disaster responders to have the access to the Internet to share real-time multimedia information with off-site commanders and specialists providing expert assistance. However, these communication services are not available in the current public safety LMR. Whereas in commercial cellular networks, less service availability means less revenues; in public safety arena, less service availability may impact lives. Therefore, it is attractive to enhance the interoperability of these two wireless networks, by which a wide variety of benefits can be offered to disaster responders, including new multimedia services (e.g., video), increased user data rates and low cost devices.

In the interoperable cellular and public safety LMR networks, disaster responders can access the services in cellular networks that are not available in public safety LMR networks to increase the service availability. Furthermore, when a disaster responder moves out of the coverage of public safety LMR networks with an ongoing communication session, the session should be handoffed to cellular networks instead of being dropped to provide the communication continuity.

In this paper, we study to enhance the interoperability between cellular and LMR networks based on Session Initial Protocol (SIP) [24] and a joint radio resource management framework. SIP is designed by the Internet Engineering Task Force (IETF) to provide application-layer signaling for voice and multimedia session management. Several wireless technical fora (e.g., 3GPP, 3GPP2, MWIF) have agreed to use SIP to provide session management. Moreover, since multimedia applications are resource-intensive in wireless networks, radio resource management is one of the major challenges in designing the interoperable cellular and public safety LMR networks. We propose a joint radio resource management framework in interoperable wireless cellular and public safety LMR networks to manage the overall radio resource in these
two heterogeneous networks. In addition, an optimal radio resource management scheme is proposed to maximize radio resource utilization and at the same time guarantee service availability and continuity quality of service (QoS) for disaster responders.

The rest of the paper is organized as follows. Section II describes the interoperable cellular and public safety LMR networks. Section III presents the joint radio resource management framework. Section IV presents the optimal radio resource management scheme. Some numerical examples are given in Section V. Finally, we conclude this study in Section VI.

II. INTEROPERABLE CELLULAR AND PUBLIC SAFETY LMR NETWORKS

A common Internet Protocol (IP)-based core network can be used to bridge cellular networks and LMR networks. In this section, we describe the IMS architecture in 3G cellular networks. Then the interoperable cellular and public safety LMR networks are presented.

A. IP-Based Networks in Wireless Cellular Networks

IP Multimedia Subsystem (IMS) [25] is introduced in the 3GPP architecture release 5 and is being updated in releases 6 and 7. This is a key evolution of the core networks as it opens 3G networks to the seamless provision of multimedia services. The 3GPP defines the IMS as the component that must provide support for multimedia services (e.g., voice and video) on IP with QoS and authentication, authorization, and accounting (AAA) provision.

Fig. 1 shows a general view of the IMS signaling architecture. The signaling network is composed of a set of call session control function nodes (CSCFs). They are signaling proxies whose task is to establish, modify, and release media sessions with guaranteed QoS and AAA and charging (AAAC) support. The tasks of the CSCFs include functionalities of SIP proxies, but are not limited to the above mentioned QoS and AAAC tasks. There are several types of CSCFs: proxy CSCF (P-CSCF, which acts on behalf of the mobile terminal in the IMS), serving CSCF (S-CSCF, which implements user registration and session control), and interrogating CSCF (I-CSCF, with proxy and topology hiding functions between operators). The home subscriber server (HSS) is similar to the home location register (HLR) in a GSM network: a centralized database that stores user authentication and profile information. Moreover, application servers (ASs) can be connected to the IMS in order to provide advanced services.

SIP is the core protocol chosen by 3GPP to perform signaling tasks in the IMS. SIP is a general-purpose application layer protocol designed to establish, modify, and release sessions in IP networks. SIP is not a vertically integrated communications system. SIP is rather a component that needs to be used with other IETF protocols (e.g., RTP and RTCP) to build a complete multimedia architecture. SIP supports five basic aspects of multimedia sessions: user location, user availability, user capabilities, session negotiation and session management.

B. Interoperable Cellular and Public Safety LMR Networks

The IMS scope is now extended in Release 7 standardization for other access networks. To provide the interoperability between cellular and public safety LMR networks, LMR networks can be treated as other access networks within the IMS framework. Fig. 2 presents the interoperability model used in this paper, showing the signaling interfaces between both networks. A general network model is used for public safety LMR networks. In the figure, the I-CSCF proxy as the signaling entry point in the interconnection between cellular and public safety LMR networks, according to the 3GPP CSCF’s role definition [25].

Since natural disasters or terrorist attacks often occur in a localized region, we assume that the coverage of the LMR is under the coverage of the cellular network, which provides a wide area coverage. The mobile devices used by disaster responders can access both the LMR and the cellular network within the coverage of the LMR. However, for commercial users, only the cellular network can be accessed. IP-based multimedia services (e.g., video streaming) are available to disaster responders via the cellular network, and mission-critical services (e.g., tactical group voice) are provided to them via the LMR. Since disaster responders are free to move in the interoperable LMR/cellular systems, the support of handoff between these two networks, which provides ongoing service continuity, is needed in this integration. In this interoperable system, disaster responders are efficiently communicated with state-of-the-art applications during a disaster.
III. Joint Radio Resource Management in Interoperable Cellular and Public Safety LMR Networks

Radio spectrum is one of the most important resources in wireless networks. Multimedia applications are resource-intensive in wireless networks. To provide good quality of service to the end users and optimally utilize the overall radio resource, radio resource management simultaneously is one of the major challenges in designing the interoperable cellular and public safety LMR networks.

In this paper, we propose a joint radio resource management framework in interoperable wireless cellular and public safety LMR networks. The framework can be used to manage the overall radio resource in these two heterogeneous networks.

A. QoS in Interoperable Cellular and Public Safety LMR Networks

Service availability and continuity are important issues in public safety arena, because less service availability and continuity may impact lives during disasters. In the interoperable systems, the key session-level QoS measures, $P^N$, new session blocking probability, and $P^H$, handoff (from LMR to cellular networks) dropping probability, experienced by disaster responders, should be kept below a target value.

For simplicity of the presentation, we consider an interoperable LMR cellular system with a single LMR cell and a single cellular cell. Disaster responders can access both the LMR and the cellular networks, whereas commercial users can only access the cellular network. When a first responder moves out of the coverage of the LMR with an ongoing communication session in the LMR, the session can be handoffed to the cellular network if resource is available there. There are $J$ classes of traffic. Class $j$, $j = 1, 2, \ldots, J$, new sessions arrive according to a Poisson distribution with the rate of $\lambda_{c,n,j}(\lambda_{l,n,j})$ in the cellular (LMR) area. Class $j$ handoff sessions depart from the LMR to the cellular network according to a Poisson distribution with rate of $\mu_{l,h,j}$. Session duration time for class $j$ traffic is exponentially distributed with the mean $1/\mu_{c,t}(1/\mu_{l,t})$ in the cellular (LMR) area. In the LMR, for class $j = 1, 2, \ldots, J$ mobile devices used by disaster response personnel, the new session blocking probability, $P^N_j$ should be kept below a target value $TP^N_j$ to guarantee the service availability.

$$P^N_j \leq TP^N_j.$$  \hspace{1cm} (1)

The handoff (from the LMR area to the cellular area) dropping probability, $P^H_j$ should be kept below a target value $TP^H_j$ to guarantee the service continuity.

$$P^H_j \leq TP^H_j.$$  \hspace{1cm} (2)

Assume that there are totally $C$ channels in the LMR. The number of channels used by a class $j$ session is $c_j$. Let $n_{i,j}$ denote the number of active class $j$ users in the LMR. Define a vector

$$x_i = (n_{1,1}, n_{1,2}, \ldots, n_{1,J}).$$  \hspace{1cm} (3)

The admissible set in the LMR can be expressed as

$$X_L = \left\{ x_i \in \mathbb{Z}^J_+: \sum_{j=1}^{J} n_{i,j}c_j \leq C \right\}.$$  \hspace{1cm} (4)

An important physical layer QoS requirement in cellular networks for class $j$ users is the signal-to-interference ratio, $\text{SIR}_j$, which should be kept above the target value $\omega_j$. In this paper, we consider WCDMA cellular system with variable spreading gain \cite{20}. Let $W$ denote the total cell bandwidth. The average bit rate of a class $j$ user is $R_j$. The orthogonality factor is $\rho$. The ratio between intercell interference and total intracell power is $\gamma$. The path loss of user $i$ is $L_i$. Let $n_{c,j}$ denote the number of active class $j$ users in the cellular network. The downlink capacity can be evaluated using cell load factor, which is defined as $\eta = \sum_{j=1}^{J} \sum_{i=1}^{n_{c,j}} (\rho + \gamma)/(W/\omega_j R_j) + \rho$. The transmit power needed at the base station to guarantee the SIR requirements is

$$P_T = \frac{P_p + P_N \Lambda}{1 - \eta},$$  \hspace{1cm} (5)

where $P_p$ is the power used by common control channels, $P_N$ is the background noise power. $\Lambda = \sum_{j=1}^{J} \sum_{i=1}^{n_{c,j}} L_i/(W/\omega_j R_j) + \rho$. Define a vector

$$x_c = (n_{c,1}, n_{c,2}, \ldots, n_{c,J}).$$  \hspace{1cm} (6)

The admissible set in the cellular network can be expressed as

$$X_C = \{ x_c \in \mathbb{Z}_{+}^J : P_T \leq P_T^{MAX} \},$$  \hspace{1cm} (7)

where $P_T$ is defined in (5) and $P_T^{MAX}$ is the maximum available power of the base station.
B. Joint Radio Resource Management

In the interoperable networks, define the state vector of the systems as \( x = (x_l, x_c) \). The state space \( X \) is defined in (4) and (7). The state space \( X \) of the interoperable system is given as

\[
X = \{ x = [x_l, x_c] \} = \{ n_l, n_c \} = \mathbb{Z}_+^J, \quad J = \sum_{j=1}^J n_{l,j}c_j \leq C, P_T \leq P_T^{MAX}\},
\]

where \( C \) is the capacity in the LMR, \( P_T \) is defined in (5) and \( P_T^{MAX} \) is the maximum available power of the cellular base station.

For each given state \( x \in X \), an action \( a(x) \) is performed by a joint radio resource management scheme. The action space is a set of all possible actions. The action is done according to a joint radio resource management scheme \( u \in U \), where \( U \) is defined as

\[
U = u : X \rightarrow A.
\]

\( \{x(t), u\}_{t \in \mathbb{R}_+} \) is a Markov process under each radio resource allocation scheme. Let \( \pi_u(x) \) denote the equilibrium probability that the system is in state \( x \) under scheme \( u \). Define \( e_{l,j} \in \{0,1\}^J \) as a row vector containing only zeros except for the \( j \)-th component, which is 1. \( x + (-)e_{l,j} \) corresponds to an increase (decrease) of the number of class \( j \) connections in the LMR by 1. \( e_{c,j} \in \{0,1\}^J \) is defined similarly for the cellular network. The global balance equations for the Markov Chain under scheme \( u \) are [27]

\[
\sum_{j=1}^J [\pi_u(x - e_{l,j}) \Lambda_{l,j}a_j(x - e_{l,j})] + \pi_u(x - e_{c,j}) \Lambda_{c,j}a_j(x - e_{c,j}) + \pi_u(x + e_{l,j}) \mu_{l,j}(n_{l,j} + 1) + \pi_u(x + e_{c,j}) \mu_{c,j}(n_{c,j} + 1) = \sum_{j=1}^J \Lambda_{l,j}a_j(x) + \mu_{l,j}(n_{l,j} + 1)\pi_u(x) + \sum_{j=1}^J \Lambda_{c,j}a_j(x) + \mu_{c,j}(n_{c,j} + 1)\pi_u(x), \quad x \in X,
\]

where \( \Lambda_{l,j}, \Lambda_{c,j}, 1/\mu_{l,j} \) and \( 1/\mu_{c,j} \) are class \( j \) connection arrival and departure rates in the LMR and cellular network, respectively. These global balance equations can be solved using any linear equation procedure, such as Jacobi and Gauss-Seidel methods. Once the equations are solved, network layer blocking probability QoS, can be directly calculated. The blocking probability for a class \( j \) connection is

\[
P^b_j = \sum_{i \in X_j} \pi(i),
\]

where \( X_j \subseteq X \) is the set of states that system will move out of \( X \) with addition of one connection of class \( j \). This approach is general enough to be applicable to a variety of radio resource allocation schemes.

However, there is a problem with the above approach. The computation complexity of solving the global balance equations is extensive when the cardinality of the state space is large. Feasible solutions are difficult to obtain in real networks due to the problem of large dimensionality. We can consider a set of coordinate convex schemes that have a product form of the equilibrium probabilities. The coordinate convex schemes form several important resource allocation schemes, such as complete sharing, complete partitioning and threshold schemes. The name of coordinate convex scheme comes from the concept of coordinate convex set. A coordinate convex scheme is characterized by a coordinate convex set, which is any nonempty set \( \Delta \subseteq X \) with the following property: if \( x \in \Delta \) and \( n_j > 0 \) then \( x - e_j \in \Delta \). In a coordinate convex scheme associated with coordinate convex \( \Delta \), a connection arrival is admitted to the system if and only if the system state remains in \( \Delta \) after the admission. The equilibrium probabilities of the system can be obtained from the theory of multiservice loss networks.

\[
\pi(n) = \begin{cases} 
\pi_0 \prod_{j=1}^J \frac{\lambda_j}{\mu_j}^{n_j}, & \text{if } n \in \Delta, \\
0, & \text{otherwise},
\end{cases}
\]

where \( \pi_0 \) is a normalization constant,

\[
\pi_0 = \frac{1}{\sum_{n \in \Delta} \prod_{j=1}^J \frac{\lambda_j}{\mu_j}^{n_j}},
\]

IV. Optimal Radio Resource Management

The above joint radio resource management schemes may not be able to maximize the radio resource utilization and guarantee the service availability and continuity QoS simultaneously. In this section, we propose an optimal radio resource management scheme that can achieve this goal. Specifically, the problem is formulated as a semi-Markov decision process (SMDP) [28]. An optimal solution can be obtained from a linear programming algorithm in this formulation.

In the interoperable network, when a new or handoff session arrives, a decision must be made as to whether or not to admit and to which network (LMR or cellular network) to admit the session request based on the current state of the system. In the SMDP framework, these decision time instants are called decision epochs. The state information is the number of sessions of each class of traffic in the system. The optimality criterion for the SMDP is the long-run average reward per unit time.

A. SMDP formulations

The system state vector at decision epoch \( t \) can be defined as

\[
x(t) = [x_l(t), x_c(t)],
\]

where
where $x_l, x_c$ are defined in (3), (9), respectively.

Similar to [29], we choose the decision epochs to be the set of all session arrival and departure instance. At each decision epoch $t_k, k = 0, 1, 2, ...$, the network makes a decision in the time interval $(t_k, t_{k+1}]$, which is referred to as an action. Action $a(t_k)$ is defined as

$$a(t_k) = [a_{t,n}(t_k) \in \{-1, 0, 1\}^J, a_{c,n}(t_k) \in \{0, 1\}^J, a_{l,h}(t_k) \in \{0, 1\}^J],$$  \hspace{1cm} (15)

where $a_{t,n}(t_k), a_{c,n}(t_k), a_{l,h}(t_k)$ are defined and interpreted as follows. 1) Define row vector $a_{t,n}(t_k) = [a_{t,n,1}(t_k), a_{t,n,2}(t_k), \ldots, a_{t,n,J}(t_k)]$, where $a_{t,n,j}(t_k)$ denotes the action for class $j$ new session arrivals in the LMR area. If $a_{t,n,j}(t_k) = 1$, a new class $j$ session that arrives in the LMR area is admitted to the cellular network. If $a_{t,n,j}(t_k) = 0$, it is rejected. 2) Define row vector $a_{c,n}(t_k) = [a_{c,n,1}(t_k), a_{c,n,2}(t_k), \ldots, a_{c,n,J}(t_k)]$, where $a_{c,n,j}(t_k)$ denotes the action for class $j$ new session arrivals in the cellular area. If $a_{c,n,j}(t_k) = 1$, a new class $j$ session that arrives in the cellular area is admitted to the LMR area. If $a_{c,n,j}(t_k) = 0$, it is rejected. 3) $a_{l,h}(t_k)$ is defined similarly for handoff session arrivals to the cellular area. If $a_{l,h,j}(t_k) = 1$, a handoff class $j$ session from the LMR to the cellular area is admitted to the cellular network. If $a_{l,h,j}(t_k) = 0$, it is dropped. For a given state $x \in X$, a selected action should not result in a transition to a state that is not in $X$. In addition, action $(0, 0, \ldots, 0)$ should not be a possible action in state $(0, 0, \ldots, 0)$. Otherwise, the system cannot evolve.

The action space of a given state $x \in X$ is defined as

$$A_x = \{a \in A_x : a_{t,n,j} \neq 1 \text{ and } x \notin X, a_{t,n,j} \neq -1, a_{c,n,j} = 0 \text{ and } a_{l,h,j} = 0 \text{ if } x_{l,n}(x + e_j) \notin X, j \in 1, 2, \ldots, J \text{ and } a \neq (0, 0, \ldots, 0) \text{ if } x_{l,n}(x + e_j) \notin X, j \in 1, 2, \ldots, J, \text{ and } a \neq (0, 0, \ldots, 0) \},$$  \hspace{1cm} (16)

where $e_j \in \{0, 1\}^J$ denotes a row vector containing only zeros except for the $j$th component, which is 1. $x_l + e_l$ corresponds to an increase of the number of class $j$ sessions by 1 in the LMR, $x_c + e_c$ corresponds to an increase of the number of class $j$ sessions by 1 in the cellular cell.

The state transition probabilities of the embedded chain and the expected sojourn time $\tau_x(a)$ for each state-action pair can be used to characterize the dynamics of the system. $\tau_x(a) = \sum_{j=1}^{J} \left[ \lambda_{l,n,j} a_{l,n,j} + \lambda_{c,n,j} a_{c,n,j} + \mu_{h,j} n_t,i,j + \mu_{l,j} n_{t,j} + \mu_{c,t,j} n_{c,j} \right]^{-1}.$

The state transition probabilities of the embedded Markov chain are

$$p_{xy}(a) = \begin{cases} \lambda_{l,n,j} \delta(a_{l,n,j}) \tau_x(a), & \text{if } y = [x_l + e_l, x_c] \\ S_1, & \text{if } y = [x_l, x_c + e_l] \\ \mu_{h,j} n_t,i,j \tau_x(a), & \text{if } y = [x_l, x_c + e_j] \\ \mu_{l,j} n_{t,j} \tau_x(a), & \text{if } y = [x_l + e_j, x_c] \\ S_2, & \text{if } y = [x_l + e_j, x_c] \end{cases},$$  \hspace{1cm} (17)

where $S_1 = (\lambda_{c,n,j} a_{c,n,j} + \lambda_{l,n,j} \delta(a_{l,n,j}) \tau_x(a), S_2 = (\mu_{h,j} + \mu_{l,j} (1 - a_{l,n,j}) n_{t,j} \tau_x(a), \delta(x) = 0, \text{ if } x \leq 0 \text{ and } \delta(x) = 1, \text{ if } x > 0.$

The average reward criterion is considered as the performance criterion in this paper. The blocking probability can be expressed as an average cost criterion. The reward for state-action pair $(x, a)$ can be expressed as

$$r(x, a) = \sum_{j=1}^{J} [w_{l,n,j} \delta(a_{l,n,j}) + w_{c,n,j} \delta(a_{c,n,j}) + \langle w_{c,n,j} a_{c,n,j} + w_{h,l,j} a_{l,h,j} \rangle],$$  \hspace{1cm} (18)

where $w_{l,n,j} \in \mathbb{R}^+, w_{c,n,j} \in \mathbb{R}^+$ and $w_{l,h,j} \in \mathbb{R}^+$ are the weights associated with class $j$ new sessions in the LMR network, new sessions in the cellular network and handoff sessions to the cellular network, respectively.

B. Service Availability and Continuity Constraints

The service availability (for disaster responders) constraint is that the new session blocking probability should be kept below a target value, $P_{l,j}^N \leq TP_{l,j}^N$. The service continuity (for disaster responders) constraint is that the handoff session (from the LMR to the cellular network) blocking probability should be kept below a target value, $P_{l,j}^H \leq TP_{l,j}^H$. Since we have derived the expected sojourn time $\tau_x(a)$ for a given state-action pair, the new blocking probability for class $j$ in the LMR can be defined as the fraction of the time the system is in a set of states $X_{l,n,j}^N \subset X$ and the chosen action is in a set of actions $A_{l,n,j}^N \subset A$, where $x_{l,n,j}^N \in X_{l,n,j}^N$ and $A_{l,n,j}^N = \{a \in A : a_{l,n,j} = 0\}$. The above derivation follows from the Poisson arrival see time averages (PASTA) theorem, which requires Poisson arrivals. Therefore, the blocking probability constraints in the system can be addressed in the linear programming formulation in (21) by defining cost functions related to service availability constraints,

$$e_{l,n,j}^N(x, a) = 1 - |a_{l,n,j}|, j = 1, 2, \ldots, J.$$

Similarly, we can define cost functions related to the service continuity constraints,

$$e_{h,l,j}^N(x, a) = 1 - a_{l,h,j}, j = 1, 2, \ldots, J.$$

C. Linear Programming Solution

The optimal policy $u^*$ of the SMDP is obtained by solving the following linear program.

$$\max_{z_{x,a} \geq 0, x \in X, a \in A_x} \sum_{x \in X} \sum_{a \in A_x} r(x, a) \tau_x(a) z_{x,a}$$
subject to
\[
\sum_{a \in A_y} z_{ya} - \sum_{x \in X} \sum_{a \in A_x} p_{xy}(a) z_{xa} = 0, \quad y \in X
\]
\[
\sum_{x \in X} \sum_{a \in A_y} z_{xa} = 1,
\]
\[
\sum_{x \in X} \sum_{a \in A_x} (1 - |a_{l,n,j}(x)|) z_{xa} \tau_x(a) \leq TP_{i,j}^N,
\]
\[
\sum_{x \in X} \sum_{a \in A_x} (1 - a_{l,h,j}(x)) z_{xa} \tau_x(a) \leq TP_{i,j}^H.
\]

The decision variables are \( z_{xa}, x \in X, a \in A_x \). The term \( z_{xa} \tau_x(a) \) can be interpreted as the steady-state probability of the system being in state \( x \) and \( a \) is chosen. The first constraint is a balance equation and the second constraint can guarantee that the sum of the steady-state probabilities to be one. The new session blocking probabilities in the LMR are expressed in the second constraint to guarantee the service availability of the disaster responders. The handoff (from the LMR to the cellular network) blocking probabilities are expressed in the third constraint to guarantee the service continuity of the disaster responders. Since sample path constraints are included in (21), the optimal policy obtained will be a randomized policy: The optimal action \( a^* \in A_x \) for state \( x \) is chosen probabilistically according to the probabilities \( z_{xa}/\sum_{a \in A_x} z_{xa} \).

V. Numerical Results and Discussions

In this section, numerical examples are used to illustrate the performance of the proposed schemes. Performance of the proposed schemes are compared with the existing scheme, in which the LMR is not interoperable with the cellular network. We show that the proposed interoperable system can significantly improve the service availability and continuity QoS for disaster responders. We also show that the scheme can guarantee the QoS constraints by keeping new service blocking and handoff dropping probabilities below some target values. To guarantee the QoS requirements, some bandwidth should be reserved in the cellular network. The optimal reserved bandwidth will also be given in this section.

We consider a LMR/cellular interoperable system with a single LMR cell and a single cellular CDMA cell. One class of video traffic is considered. The data rate of each video flow is 64 Kbps. We assume the capacity of the LMR is 384 Kbps. The numerical values for the system parameters are given in Table I. The new session arrival rate in the system is \( \lambda_n = \lambda_{l,n} + \lambda_{c,n} \), where \( \lambda_{l,n} \) and \( \lambda_{c,n} \) are new session arrival rates in the LMR and the cellular network, respectively. We assume that 40% of the total new session arrivals occur in the LMR area. In the numerical examples, \( \mu_{c,t} = 0.005, \mu_{l,t} = 0.002, \mu_{l,h} = 0.002 \) and \( w_{l,n} = w_{c,n} = w_{l,h} = 1 \).

A. Service Availability and Continuity QoS Improvement

Fig. 3 shows the service availability and continuity QoS in different schemes. We can see that for new sessions from disaster responders, the blocking probability in the proposed scheme is significantly less than that in the existing scheme, in which the LMR and the cellular network are not interoperable. A similar observation is true with the handoff dropping probability of disaster responders. In the existing scheme, when a disaster responder moves out of the LMR with an ongoing session, the ongoing session must be dropped. In contrast, in the proposed scheme, the ongoing session can be handoffed to the cellular network. The service availability and continuity QoS can be improved significantly in the proposed scheme compared to the existing scheme.

B. Guaranteed Service Availability and Continuity QoS

The proposed scheme can also guarantee the QoS constraints, as shown in Fig. 4. In this example, the new session blocking probability QoS constraint is 3% for disaster responders. That is, the new session blocking probability for disaster responders cannot exceed 3%. The handoff dropping probability is 0.5%. From Fig. 4, we can see that the proposed scheme can always guarantee the QoS constraints with a variety of traffic loads. This is achieved by reserving some bandwidth in the cellular network for disaster responders.

C. Optimal Reserved Bandwidth

The optimal reserved bandwidth can be obtained by solving the linear program (21). Fig. 5 shows the optimal bandwidth that needs to be reserved to guarantee the QoS requirements for disaster responders. Some bandwidth is reserved exclusively for disaster responders. Some bandwidth is reserved partially for them. For example, when the new session arrival rate is 0.06, the new session arrivals from the cellular network will be rejected when there are 8 (or 9 and 10) users in the cellular network; whereas session arrivals from the LMR will always be accepted whenever some bandwidth is available. When there are 7 users in the cellular networks, the new session arrivals from the cellular network will be accepted with a probability 0.1129. This randomized policy is due to the QoS constraints, which is explained in Subsection IV-C.

VI. Conclusions and Future Work

We have studied the interoperability problem in public safety land mobile radio networks and commercial cellular

| Parameter            | Notation | Value   |
|----------------------|----------|---------|
| target SIR for video traffic | \( \omega \) | 8 dB    |
| bandwidth in the cellular network | \( W \) | 3.84 M  |
| orthogonality factor | \( \rho \) | 0.4     |
| intercell/intracell ratio | \( \eta \) | 0.35    |
| data rate for video traffic | \( R \) | 64 Kbps |
| common control channels power | \( P_p \) | -33 dBm |
| background noise power | \( P_N \) | -96 dBm |
| maximum base station power | \( P_{MAX} \) | 43 dBm |
| capacity in the LMR | \( C \) | 384 Kbps |
Service availability and continuity QoS constraints for disaster responders. The interoperability can be enhanced by using Session Initial Protocol and a joint radio resource management framework. In addition, we have formulated service availability and continuity QoS constraints for disaster responders as new session blocking probability and handoff dropping probability constraints, respectively. We have presented an optimal joint radio resource management scheme in the interoperable system to maximize the overall radio resource utilization while guaranteeing the QoS constraints.

A semi-Markov decision process formulation and linear-programming-based algorithms for computing the optimal scheme were presented. Numerical examples were used to show the performance of the proposed scheme. We have shown that the proposed scheme can significantly improve the service availability and continuity QoS for disaster responders.

Further study is in progress to evaluate the SIP-based handoff schemes in the interoperable LMR/cellular networks. Vertical handoff delay will be considered as one of the key issues. It is also interesting to consider other QoS requirements, such as packet delay and loss, in the interoperable heterogeneous wireless networks.

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