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Utility Function Selection for Streaming Videos with a Cognitive Engine Testbed

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Abstract Cognitive Radio (CR) is a new wireless communication and networking paradigm that is enabled by the Software Defined Radio (SDR) technology and the recent change in spectrum regulation policy. As the first commercial application of CR technology, IEEE 802.22 wireless regional area networks (WRAN) aim to offer broadband wireless access by efficiently utilizing the unoccupied TV channels. In this paper, we investigate the problem of utility function selection and its impact on streaming video quality through an IEEE 802.22 WRAN base station (BS) cognitive engine (CE) testbed developed at *Wireless@Virginia Tech*. We find that significant improvement on received video quality can be achieved when CE adopts a dynamic, content-aware, video-specific utility function rather than a static, predefined, general purpose utility function. This work indicates the importance of video distortion modeling and cross-layer design, and the need for employing dynamic content-aware utility functions at the CE for cognitive streaming video communication networks.

Keywords 802.22 wireless regional area network (WRAN) · cognitive engine · cognitive radio · cross-layer optimization · radio resource allocation · utility function · video streaming

1 Introduction

Cognitive Radio (CR) is a new wireless communication and networking paradigm that is enabled by the Software Defined Radio (SDR) technology [1] and recent spectrum policy reform [2, 7]. A CR node can sense the radio frequency (RF) spectrum to detect the unused or under-utilized RF spectrum (*white space*). Its frequency-agile radio module can be tuned to a detected "white space" and operate from there. The CR concept represents a significant paradigm change from exclusive use of spectrum by licensed users (or, *primary users*), to dynamic spectrum access for unlicensed users (or, *secondary users*). It may change the way how wireless communications systems are designed and operated, and drive the next generation of radio devices and wireless standards that enable a variety of new applications.

The high potential of CR has attracted significant research efforts [3, 4]. A particular progress was made with the formation of the IEEE 802.22 working group in 2004, aiming to develop point-to-multipoint *wireless regional area networks* (WRAN) standards. WRAN systems operate at the prized UHF/VHF TV bands ranging from 54 MHz to 862 MHz for broadband wireless communications. The IEEE 802.22 WRANs are

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motivated by the fact that most of the TV programs are now provided via cable or satellite networks, and the broadcast TV bands are usually underutilized. In addition, the usage of TV channels by primary users are highly predictable at a given location (i.e., regular TV program hours and fixed number of channels for a long period of time), making it relatively easier for secondary users to detect the presence of primary users and to access the spectrum. A typical IEEE 802.22 system consists of one or more *base stations* (BS) and *customer-premises equipment* (CPE). The CPEs will sense the RF spectrum and report the sensing results to the BS periodically. The BS, based on the distributed sensing results, will determine which TV channels are available for use and then intelligently allocate the radio resource to the CPEs to satisfy their quality of service (QoS) requirements and comply with all applicable spectrum policy, such as the maximum transmit power limit and RF emission masks [5].

Although SDR makes waveforms programmable, it is the intelligence, awareness, and learning capability of the CR that fully exploits its potential. The "intelligent agent" that manages cognition tasks in a CR is called a *cognitive engine* (CE) [6]. By leveraging past experience and knowledge, the CE can choose the most efficient reasoning and learning method and make (near-)optimal cross-layer adaptations subject to constraints of regulation, policy, and radio equipment capability. The CE usually takes into account the most pertinent performance metric(s) and incorporates them into a proper utility function to meet the CR's goal for the specific radio scenario or application. Therefore, the selection of appropriate performance metrics and utility functions is critical for CR performance [6].

In this paper, we evaluate the performance of an IEEE 802.22 WRAN BS CE testbed on supporting video applications. This CE testbed was developed at *Wireless@Virginia Tech* [8–10]. Video is one of the killer applications for numerous emerging (cognitive) wireless networks. As a bandwidth-hungry and distortion sensitive application, radio resource management needs to be highly efficient and intelligent among network nodes in light of the demanding (perhaps also dynamically changing) system requirements and constraints. We assume an IEEE 802.22 WRAN with a BS and multiple CPEs, while the BS is transmitting a video stream to each CPE. We assume certain feedback and rate control mechanism between the BS and the corresponding video servers, such that each server can change the bit rate of the streaming video based on feedback from the BS, in order to fully exploit the available bandwidth in the WRAN and to maximize the received video quality at the CPEs.

Specifically, we investigate the important problem of utility function selection and its impact on the received video quality. Utility functions play an important role in the convergence speed and final achievable performance of cognitive wireless networks [6]. Through testbed experiments, we compare the performance, in the form of received video distortion, achieved when two different utility functions are used in the CE. The first utility function is a generic utility function defined for supporting a variety of services to subscribers such as voice, data, and video. The second utility function is in the form of end-to-end video distortion consisting of the *encoder distortion* caused by quantization and *channel distortion* due to packet loss within the network [11–14]. We find that the video-specific utility function achieves significant improvements on received video quality, indicating the efficacy of cross-layer design and more importantly, the need for adopting dynamic application- and content-aware utility functions in the CE, rather than a predefined static one.

The remainder of this paper is organized as follows. We review the WRAN BS CE testbed architecture and key system parameters in Section 2. We then define the utility functions employed in the testbed experiments in Section 3. Our experimental results are present in Section 4. Section 5 discusses related work and Section 6 concludes this paper.

2 WRAN BS CE testbed architecture and key parameters

As discussed, IEEE 802.22 WRAN is the first commercial application of CR technology, aiming to offer broadband wireless access by efficiently utilizing "white spaces" in the broadcast TV bands [5, 15]. In this section, we describe the architecture and key system parameters of a WRAN BS CE testbed developed at Wireless@Virginia Tech [8–10], which will be used in our experimental study of streaming video over CR networks.

As shown in Fig. 1, the WRAN BS consists of a spectrum sensing module, a Radio Environment Map (REM), the CE, and a software defined radio (SDR) transceiver. The spectrum sensing module is used to sense the presence of primary users in the neighborhood, while the sensing results will be recorded in the REM. The REM is basically a comprehensive database designed for providing network-wide situation-awareness [16, 17]. The CE, as the "brain" of network radio resource management, may incorporate various learning and reasoning methods such as case- and knowledge-based learning (CKL), a channel modeler

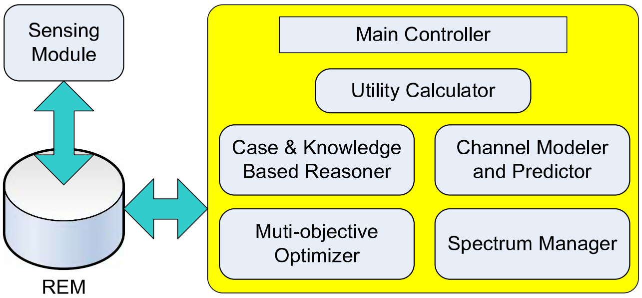


Fig. 1 Architecture of the REM-based CE for an IEEE 802.22 WRAN BS

and predictor, a multi-objective optimizer, a spectrum manager and other functional entities [8–10]. The CE first obtains situation awareness by spectrum sensing (i.e., is there any active primary user in the neighborhood?) and by querying the REM. It then determines the utility function that best fits the current situation for radio resource management [6, 10].

The multi-objective optimizer in the CE is implemented with genetic algorithms (GA) [18]. GA is a population-based metaheuristic inspired by the *survival-of-the-fittest* principle. GA is particularly suitable for solving complex combinatorial optimization problems, most of which are multi-modal and nonconvex. In GA, a solution is coded in the form of *chromosome*, and several genetic operators such as *crossover* and *mutation* are adopted to change the chromosomes to guide the search in the solution space, while selection of competitive solutions is based on their *fitness* (in the form of an objective, or utility function). The survival-of-the-fittest principle ensures that the overall quality of the population improves as the algorithm progresses from one generation to the next.

A section of the chromosome for the GA-based WRAN CE is shown in Fig. 2. The size of the chromosome (in bits), and hence the computational complexity, increases with the number of new connections, the number of adaptable parameters ("knobs") of the CR

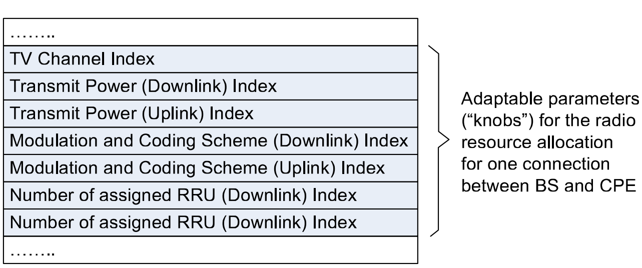


Fig. 2 A section of the chromosome for the GA-based WRAN CE

node, and the adaptation range of each "knobs." The GA-based multi-objective optimizer helps the CE to achieve multiple goals (such as minimizing voice/video distortion and maximizing spectrum efficiency) subject to various practical constraints (such as the maximum transmit power limit and RF emission masks) [5].

For WRAN systems, the distributed CPEs may request different types of services, such as voice, data, and video. To facilitate efficient radio resource management, the WRAN BS CE needs to know the amount of radio resource that is required to setup a new connection for a CPE. To obtain a generic and convenient measure of the available radio resource at the BS and the requested radio resource from CPEs, a unitless metric—*Radio Resource Unit* (RRU)—is introduced and employed in the WRAN BS CE testbed. For example, the required RRU (RRU_{req}) for a new connection can be estimated by

$$RRU_{req} = (1+\alpha)\frac{R}{\eta \cdot BW_{sc}}, \tag{1}$$

where α is the overhead factor (unitless) that accounts for the overhead of the WRAN protocol and can be determined from the WRAN system specification; R is the data rate of the new connection (unit: bps) and determined by the service type; η is the spectral efficiency (unit: bps/Hz) jointly determined by the highest applicable modulation level and channel coding rate; BW_{sc} is the bandwidth of the WRAN OFDM subcarrier (unit: Hz) defined as

$$BW_{sc} = \frac{\text{TV Channel Bandwdith}}{\text{FFT Mode}}, \tag{2}$$

More specifically, in the context of the OFDM modulation format assumed for the WRAN, the physical meaning of RRU_{req} is the number of OFDM subcarriers to be allocated per WRAN frame for a given service request from the CPE. Equation 1 takes into account the WRAN protocol overhead. Intuitively, the larger the associated protocol overhead, the more RRUs will be required. The spectral efficiency of several typical modulation and coding schemes used in WRAN systems are given in Table 1.

Considering the inherent cognition and interference avoidance capability of WRANs, the WRAN BS CE estimates the signal-to-noise ratio (SNR) without considering any type of interference. The modulation and coding scheme is selected based on the estimated SNR level at the receiver under additive white Gaussian noise (AWGN), assuming the radio link between the BS and CPE is (quasi-) static.

Table 1 Spectral efficiency of several modulation and coding schemes for WRAN

Modulation Level	Coding rate	Spectral efficiency (bps/Hz)
QPSK	1/2	1
QPSK	3/4	1.5
QPSK	1 (no coding)	2
16QAM	1/2	2
16QAM	3/4	3
16QAM	1 (no coding)	4
64QAM	2/3	4
64QAM	3/4	4.5
64QAM	1 (no coding)	6

3 Definition of utility functions

As discussed, utility functions are used in the CE for radio resource management. The selection of utility functions is critical for CE to achieve the desired performance, since they determine the convergence and optimality of the solutions produced by the multi-objective optimizer in the CE. In this section, we describe two types of utility functions for the WRAN BS CE testbed, a generic utility function that can be used for general WRAN applications and an application-specific utility function for video over CR networks.

3.1 Performance metrics and the global utility function

When defining utility functions for CE, the first step is to choose or define proper *performance metrics*, which can then be incorporated into a utility function. The following performance metrics are adopted for the WRAN BS CE testbed [6, 8, 9].

- u_1 = QoS satisfaction of all connections, in terms of the average utility of all downlink and uplink connections between CPEs and the BS.
- u_2 = spectral efficiency, in terms of the number of candidate channels or the total amount of RRU assigned per active TV channel. This metric is more important for multi-cell scenarios or a single cell with a large number of CPEs.
- u_3 = power efficiency, in terms of the transmit power of individual CPEs. This metric is more important for mobile or portable user devices or overlapping WRANs operated by different service providers.

The utility function employed by the CE is usually defined as a weighted combination of multiple selected performance metrics. To be flexible for various radio scenarios or applications, a viable approach for the CE is to adopt dynamic situation-aware utility functions rather than a predefined static one. In general, the *global utility function* for the WRAN BS CE can be defined as

$$u_{global} = \prod_i (u_i)^{\omega_i}, \tag{3}$$

where ω_i is the weight applied to the i-th performance metric (u_i). Different weight vectors could be applied to adjust the utility function. Similar to the geometric mean, this definition of u_{global} accentuates low utility metrics, thus providing a fair and balanced combination of various performance metrics.

For the WRAN BS CE testbed, the global utility (u_{global}) is subdivided between individual CPE utilities (u_{cpe}) and the normalized spectral efficiency of the BS (u_{BS}) as

$$u_{global} = \left[\prod_i^N \left(u_{cpe,i}\right)^{\omega_{cpe}/N}\right] \cdot (u_{BS})^{\omega_{BS}}, \tag{4}$$

where N is the number of active CPEs currently associated with the WRAN BS, and ω_{cpe} and ω_{BS} are the weight for the geometric mean of individual CPE utilities and the weight for the spectral efficiency of the BS, respectively. The weights (ω_{cpe} and ω_{BS}) can be determined by the WRAN operator based on its priority and goal. For the experiments reported in this paper, ω_{cpe} is set to 0.9 and ω_{BS} is set to 0.1.

3.2 A generic utility function for CPEs

To accommodate multiple applications, a generic utility function proposed for individual CPE is defined as

$$u_{cpe} = \left[f_1(P_b^{-1}, P_{b_0}^{-1})\right]^{0.5} \left[f_2(R_b, R_0)\right]^{0.4} \left[f_3(P_t^{-1}, P_{t_0}^{-1})\right]^{0.1}, \tag{5}$$

where P_b, R_b, and P_t are the measured or estimated bit-error-rate, data rate, and transmit power of the CPE, respectively; and P_{b_0}, R_0, and P_{t_0} are the target bit-error-rate, data rate, and transmit power of the CPE, respectively. The utility function f_i's are modified (shifted and spread/compressed) hyperbolic tangent functions, i.e.,

$$f_i(x, x_0; \eta_i, \sigma_i) = \frac{1}{2}\left\{\tanh\left[\log\left(\frac{x}{x_0}\right) - \eta_i\right] \cdot \sigma_i + 1\right\}, i = 1, 2, 3, \tag{6}$$

where x and x_0 are the performance metric and the target value, respectively; and η_i and σ_i are the threshold and the spread parameter, respectively. The utility function f_i is monotone and bounded by 0 and 1, as shown in Fig. 3. For the WRAN BS CE testbed, the

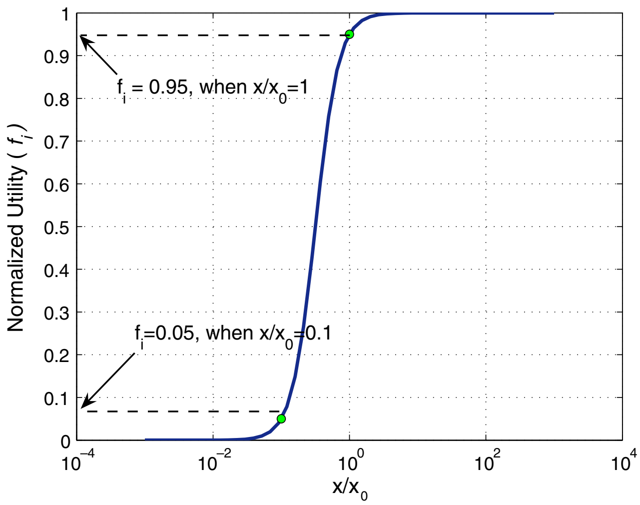


Fig. 3 Illustration of the CPE utility function f_i, a modified hyperbolic tangent function

threshold (η_i) and spread parameter (σ_i) are chosen such that

- the utility is 0.95 when the performance metric (x) achieves the target value (x_0), and
- the utility is 0.05 when the performance metric is one decade below the target value.

Note that the individual CPE utility function (6) represents the degree of satisfaction of the user to the overall radio resource management. The modified hyperbolic tangent function is a type of *sigmoid function* that can accommodate a large range of performance variations and capture the value of the service to the user quite naturally. If the solution does not meet the target goal, the utility is decreased sharply. On the other hand, since solutions that result in excessively high QoS provide little extra value to the user, the increase of utility is marginal when x is within this range.

3.3 A video-specific utility function for CPEs

Our second choice of utility function for CPEs is a video application-specific one, which is defined as a function of the estimated mean squared error (MSE) distortion based on an empirical rate-distortion model for streaming videos. We consider the distortion of a received video, which largely consists of the encoder distortion (D_e), caused by quantization, and channel distortion (D_c) due to packet loss within the network [11, 12]. The end-to-end video distortion is

$$D = D_e + D_c. \tag{7}$$

Based on the rate-distortion theory and experimental studies, many empirical models have been introduced in the literature [11, 12, 19–22]. We adopt the model proposed in [11] in this paper without loss of generality. Under this model, the encoder distortion, measured as MSE, can be evaluated by:

$$D_e = \phi + \frac{\theta}{R - \lambda}, \tag{8}$$

where ϕ, θ and λ are constants for a specific video codec and video sequence, and R is the coding bit rate. We verify this model using the H.264 codec with options in the Baseline profile and the Quarter Common Intermediate Format (QCIF) *Foreman* test sequence. The measured distortion and the computed distortion using Eq. 8 are plotted in Fig. 4, where excellent match can be observed.

The second component of D, namely, channel distortion D_c, is caused by packet loss within the network. We adopt the general model presented in [12] for channel distortion, which has the following simplified form (i.e., an upper bound):

$$D_c = \frac{p}{\beta \cdot (1-p)} D_{ECP}, \tag{9}$$

where D_{ECP} is a constant and can be predetermined by training; β is the intra rate, a coder parameter; and p is the average packet error rate (PER).

In out experimental studies, the parameters for the QCIF *Foreman* and *Football* video sequences are derived by regression analysis using H.264 coded sequences. We then adopt a video application-specific

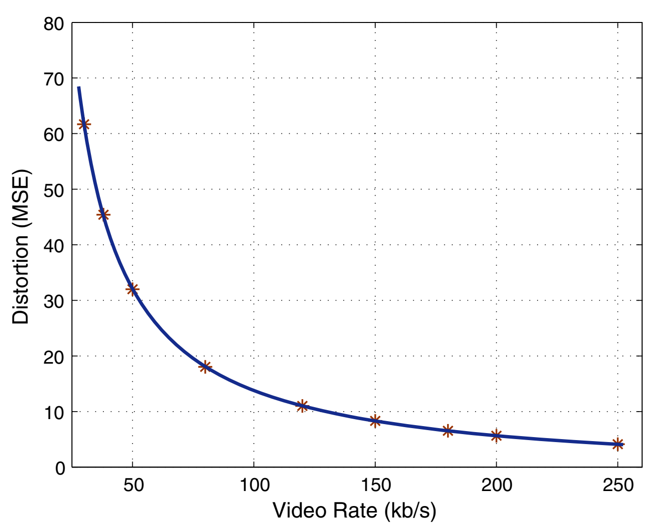


Fig. 4 Rate distortion curve at the encoder for the QCIF test sequence *Foreman*, which is encoded with an H.264 codec at 15 frames per second. The markers are measured points, while the curve is computed using Eq. 8

utility function for the CPEs, which is defined as follows:

$$u_{cpe} = \begin{cases} 1/D, \text{ if } D > 1 \\ 1, \quad \text{ if } D \leq 1. \end{cases} \tag{10}$$

Maximizing this utility for the CPEs is equivalent to minimizing the MSE distortion of received videos at the CPEs.

3.4 The BS utility function

The normalized BS spectral efficiency (u_{BS}) is determined by averaging the number of available subcarriers per WRAN channel, i.e.,

$$u_{BS} = \frac{1}{M} \sum_{i=1}^{M} u^i_{BS}, \tag{11}$$

where M is the number of channels supported by the BS, and u^i_{BS} is the spectral efficiency of the i-th WRAN channel, which also indicates the radio resource utilization of this channel at the BS, $i = 1, 2, \cdots, M$.

For the current version of the WRAN BS CE, u^i_{BS} is defined as

$$u^i_{BS} = 1 + \tanh\left(\frac{RRU_{available} - RRU_{capacity}}{\sigma_{RRU}}\right), \tag{12}$$

where $RRU_{available}$ is the number of RRUs that are available for the i-th WRAN channel at the BS, ranging from 0 to $RRU_{capacity}$; $RRU_{capacity}$ is the maximal number of subcarriers available for a WRAN channel; and σ_{RRU} is the spread parameter for the modified hyperbolic tangent function.

Figure 5 shows the u^i_{BS} employed in the WRAN BS CE testbed, where $RRU_{capacity}$ for a WRAN channel is set to 2048, and σ_{RRU} is set to 800. It can be verified that u^i_{BS} is monotone and is bounded by 0 and 1. The rationale to adopt such a modified hyperbolic tangent function as the utility function for overall WRAN BS spectrum efficiency, is that it helps the CE to squeeze the spectrum used by the WRAN BS (in terms of the number of channels or subcarriers in use) through the optimization process. For example, the solution, which assigns the CPEs to subcarriers spreaded into two or more WRAN channels, will produce a lower BS utility (u_{BS}) as compared to the more spectral efficient solution in which the CPEs are assigned to subcarriers within the same WRAN channel.

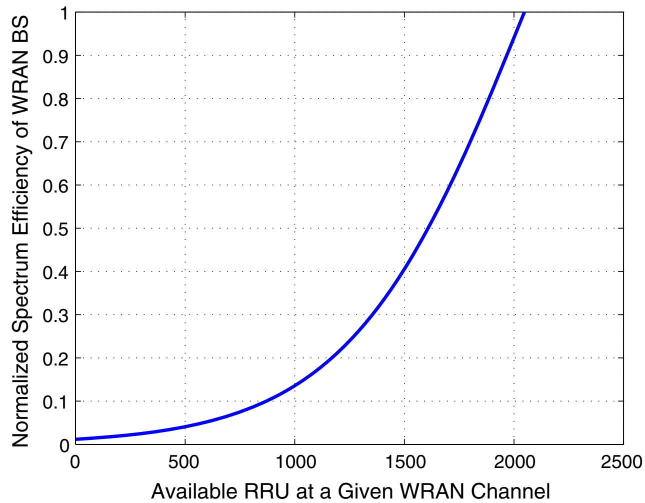


Fig. 5 Illustration of the BS spectral efficiency function employed in the WRAN CE testbed

4 Experimental system parameters and results

4.1 Testbed setting

To evaluate the performance of the WRAN CE with different utility functions, we adopt a typical WRAN scenario where fifty (50) CPEs are randomly distributed in the service area of a WRAN BS, as shown in Fig. 6. In this figure, the WRAN BS is located at the origin and the radius of the BS service area is

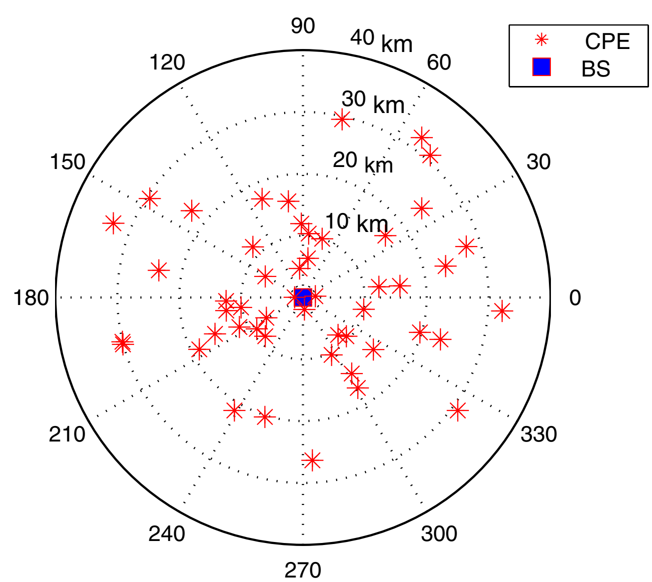


Fig. 6 The WRAN network used in our experiments. Fifty CPEs are randomly distributed in the service area of a WRAN BS with cell radius of 33 km

Table 2 Experimental parameters for the WRAN BS CE Testbed

Parameter	Value or range
Radius of WRAN BS service area	33 km
Types of service and quality of service requested by the CPEs	– Voice: target rate – 10 kbps, target BER – 10^{-2} – VIdeo: target rate – 100 kbps, target BER – 10^{-3} – Low data rate: target rate – 250 kbps, target BER – 10^{-6} – High data rate: target rate – 750 kbps, target BER – 10^{-6}
Multiplexing/duplexing	OFDMA/TDD (Downlink-Uplink ratio: 3)
Number of subcarriers per channel (FFT mode)	2,048
WRAN channel bandwidth	6 MHz

33 km. The simulation parameters for the WRAN BS CE testbed are presented in Table 2, and the requested service at each CPE is set to "video". The adjustable parameters of the testbed are listed in Table 3.

For the results reported in this section, the H.264 reference software encoder (JM) in the Baseline profile is used to encode the test video sequence in realtime. Each encoded video frame is carried in one UDP packet, so that a lost packet leads to a lost frame [12]. Without loss of generality, we use the medium motion test sequence *Foreman* in the QCIF format. The videos are encoded at 15 frames/s, while the first frame is coded in the intra-mode (i.e., an I frame) and all the remaining frames are P frames. The intra rate is $\beta = 0.03$. The distortion of the received videos are determined by the average channel distortion due to packet loss and encoder distortion, both in MSE, as given in Eq. 7.

4.2 Experiment results

Two sets of experiments are carried out to evaluate the impact of the two CPE utility functions under the same network condition. In each experiment, the CE is used to allocate radio resource to the CPEs for streaming H.264 encoded videos to each of them. During video streaming, we record the utility, average distortion of received video, average video bit rate, average video packet loss rate, and the transmit power for each CPE. The experiment results are shown in Figs. 7–16.

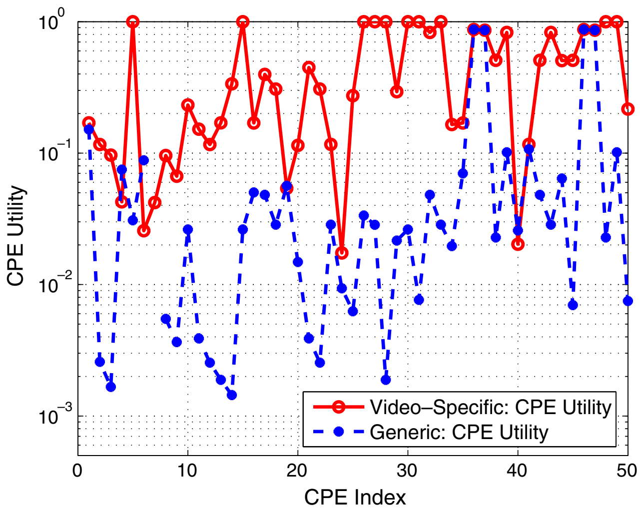
In Fig. 7, we plot the CPE utilities achieved by both CPE utility functions. Specifically, Fig. 7a is for the case when two WRAN channels are available at WRAN BS, while Fig. 7b is for the case when four WRAN channels are available. In both cases, we find that the video utility of each CPE is fairly low (less than 0.1 for most CPEs) when the generic utility function as defined in Eq. 5 is used, while using the video-specific utility function as defined in Eq. 10 can significantly increase the video utility at each CPE. For most CPEs, there is over 10 times improvement in video utility achieved by using the video-specific utility function. It is also interesting to note that using more WRAN channels does not significantly improve the video utility at the CPEs under the generic utility function, while the video-specific utility function can better exploit the increased radio resource to achieve higher utility for most of the CPEs. It can be seen with four WRAN channels, most of the CPEs achieves the maximum utility of 1 when the video-specific utility function is used.

We next plot the average MSE distortion of the received videos at the CPEs in Fig. 8, where four WRAN channels are available for use at the WRAN BS. As expected, we find the video distortion at each CPE is significantly reduced when using the video application-specific utility function, as compared to that when using the original generic utility function. In the first case, video distortion is less than 10 for all CPEs, implying excellent perceived video quality at the CPEs. Similar observation can be made in the case of different number of available WRAN channels, but are omitted for brevity.

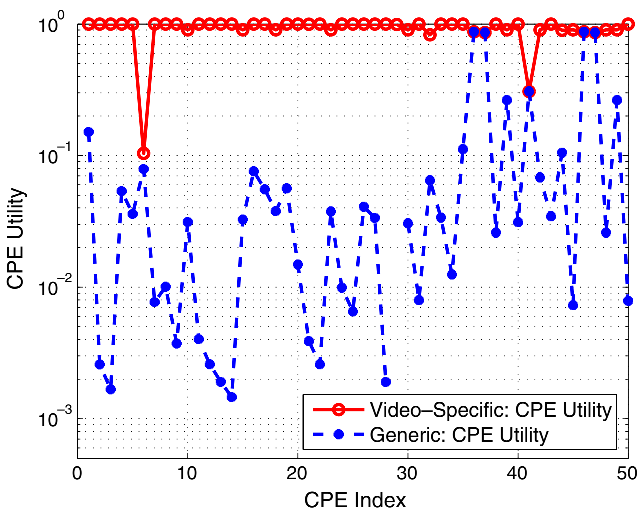
As shown in Eq. 7, the distortion of decoded video is mainly a function of the video bit rate (R) and the PER (p). To further illustrate the different performance of the two utility functions, we plot the average PER in

Table 3 Adjustable parameters ("Knobs") at the WRAN BS and CPEs

Parameter	Value or range
Channel frequency	VHF/UHF (54–862 MHz)
Maximum EIRP of BS, CPE	4 Watts
Modulation scheme	QPSK, 16QAM, and 64QAM
Channel coding	None, 1/2, 2/3, and 3/4 (convolutional coding rate)
Number of UL/DL subcarriers allocated to the new connection	Variable from 4 to 256



(a)



(b)

Fig. 7 Utilities at each CPE when using the generic utility function defined in Eq. 5 and when using the video-specific utility function defined in Eq. 10. **a** Two WRAN channels available. **b** Four WRAN channels available

Fig. 9 and the average video bit rate in Fig. 10 for each CPE. The PER is estimated at the CE as

$$PER = 1 - (1 - BER)^L, \tag{13}$$

where BER is the average bit error rate estimated at the CE according to the channel model and the modulation and coding scheme, and L is the average packet length in bits. Note that we assume that bit errors are uniformly distributed under the AWGN channel. We find in Fig. 9 that the PER at each CPE can be significantly reduced (less than 10^{-3} for most CPEs) when using the video-specific utility function, as compared to the case of using the generic utility function. Similarly,

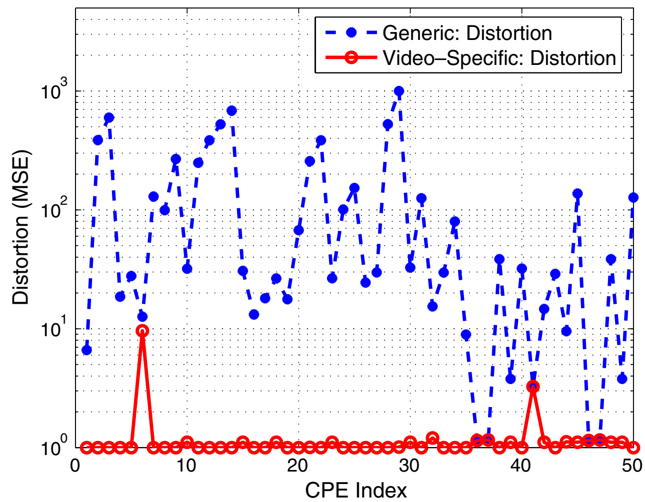


Fig. 8 Comparison of video distortions achieved by the two utility functions

we find in Fig. 10 that the assigned bit rate for each CPE can be much higher (more than 480 kbps for most CPEs) when using the video-specific utility function, as compared to the case of using the generic utility function. The joint effect of the increased bit rate and reduced PER is the improved video quality at each CPE, as observed in Fig. 8.

Figure 11 compares the achieved CPE utility when the type of streaming video is correctly identified vs. incorrectly identified by the WRAN CE. As indicated from this figure, content awareness (i.e., video type awareness) is critical for CE to select the most applicable video distortion model when defining the video-specific utility function. For the experiment results

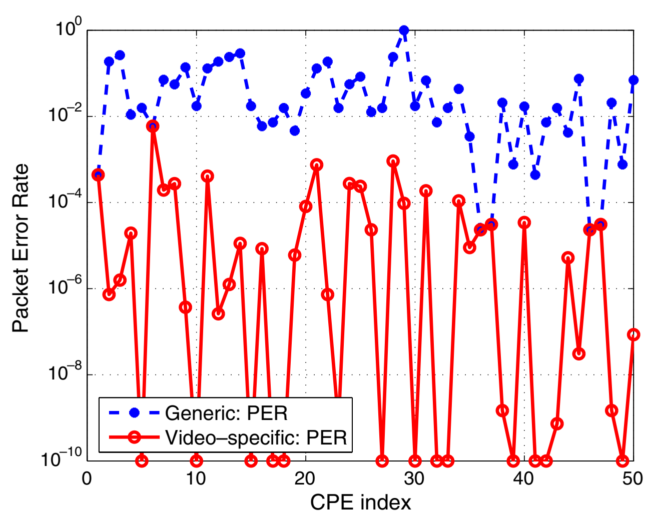


Fig. 9 Comparison of packet error rates (PER) achieved by the two utility functions

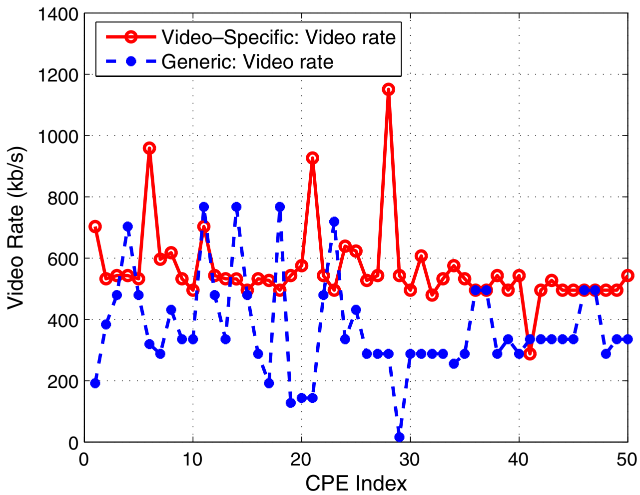


Fig. 10 Comparison of video bit rates achieved by the two utility functions

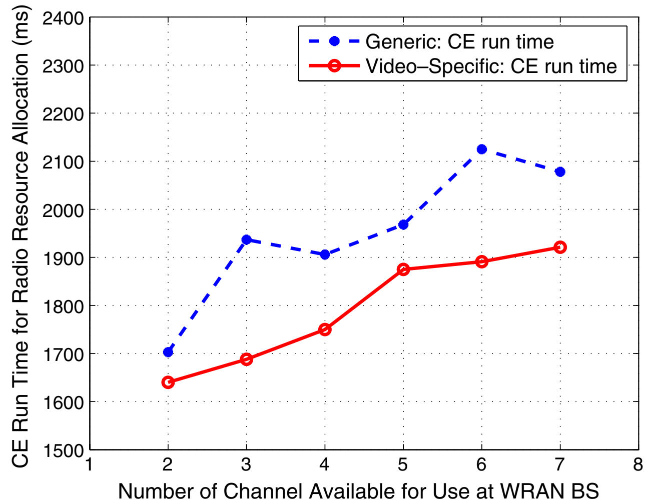


Fig. 12 Comparison of radio resource allocation time when different utility functions are employed by WRAN CE

shown in Fig. 11, it is assumed that the video type is "football". When the CE identifies the video type incorrectly, an inappropriate video distortion model (e.g., "foreman" model) will be employed instead. As a consequence, much lower video utility (i.e., larger video distortion) is resulted for most CPEs. This result reveals the importance of video content awareness for WRAN CE in order to define the most appropriate video-specific utility function.

Figure 12 compares the WRAN CE run time for radio resource allocation when different utility functions are employed. For this experiment, the WRAN CE runs on a computer with 1.66 GHz CPU and 1 GB RAM. As shown from this figure, in general, the run time for radio resource allocation by CE increases with the number of available channels at the WRAN BS, no matter which utility function is employed. The more radio channels (i.e., radio resources) available at the WRAN BS, the longer time it takes the CE to optimize radio resource allocation among all CPEs. In addition, the experiment results show that it takes longer time for CE to deliver a radio resource allocation scheme when adopting the generic utility function than that when a video-specific utility function is used. This is partly because the video-specific utility function has lower computational complexity than the generic one, as can be seen from utility functions (4)–(10). For 802.22 WRAN, an important performance metric is the channel evaculation time when primary user re-appears. Note that WRAN channel evaculation time includes not only BS radio resource re-allocation time but also radio channel switch time at BS and CPE. From the results shown in Fig. 12, it is possible to estimate the lower bound of WRAN channel evaculation time when TV or wirless microphone (i.e., primary user) signal is detected at some channel(s). For example, supposing that the WRAN BS has allocated 5 channels to CPEs, when two of them are no longer available for use due to the re-appearance of primary user(s), it takes the BS CE about 1700 ms to re-allocate the remaining radio resources to all CPEs when video-specific utility function is employed, as compared to about 1900 ms when generic utility function is adopted.

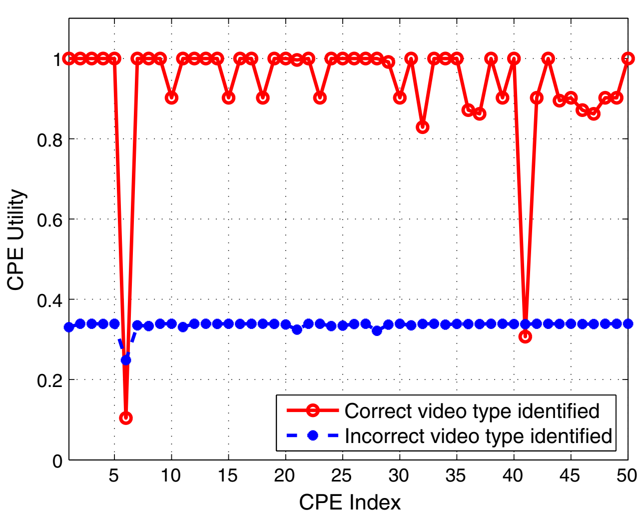


Fig. 11 Impact of content-awareness: comparison of CPE utility when video type is correctly vs. incorrectly identified by the CE

Figure 13 compares the number of channels actually allocated to CPEs when different utility functions are

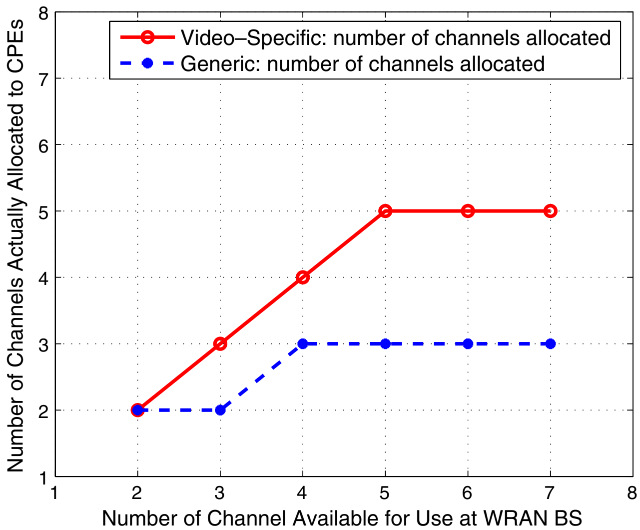


Fig. 13 Comparison of number of channels allocated when different utility functions are employed

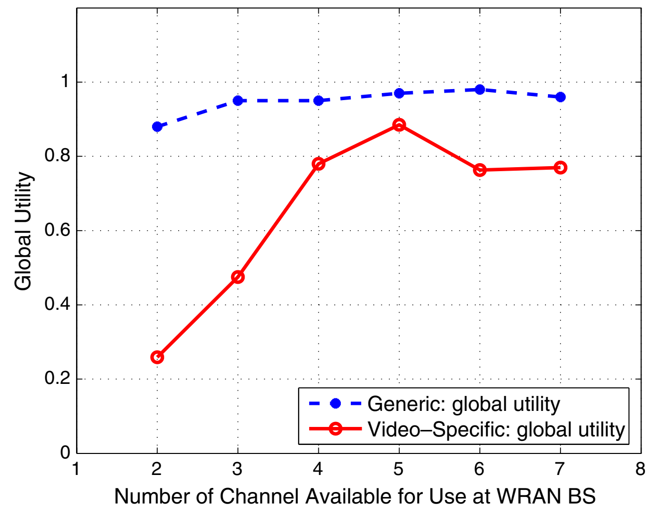


Fig. 15 Comparison of global utility achieved when different utility functions are employed

employed by the WRAN CE. It shows that when more TV channels are available for use at the BS, generally, more channels will be allocated to CPEs when video-specific utility function is employed than that when generic utility function is adopted. This result indicates that video-specific utility function can drive the WRAN CE to better take advantage of the available channels and therefore result in better video quality at CPEs. Interestingly, we also notice that, no matter which utility function is employed, the number of channels actually allocated to CPEs will not always keep increasing with the number of available channels after certain point. For example, when there are seven channels are available at WRAN BS, only three of them are actually allocated to CPEs when generic utility function is employed; and only five channels are actually allocated when video-specific utility function is used. This result is in line with our expectation, considering that the global utility of WRAN BS requires CE to make a tradeoff between CPE utility and BS spectral efficiency: using more radio channels could increase the CPE utility, but it is at the cost of reduced BS spectral efficiency as evidenced by Fig. 14.

Figure 15 compares the global utility achieved when different utility functions are employed by the WRAN

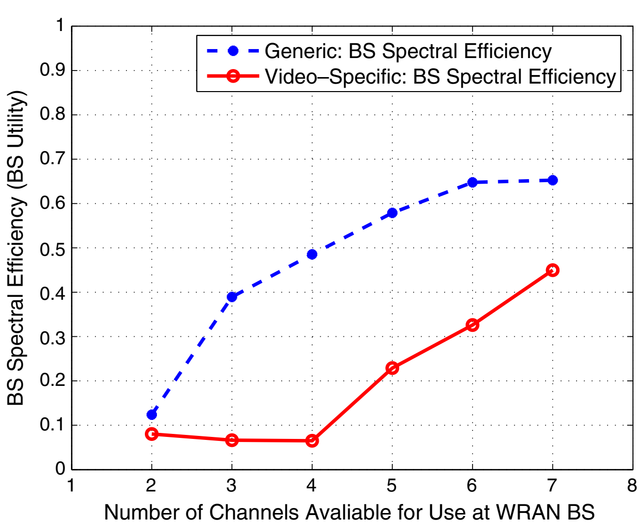


Fig. 14 Comparison of BS spectral efficiency when different utility functions are employed

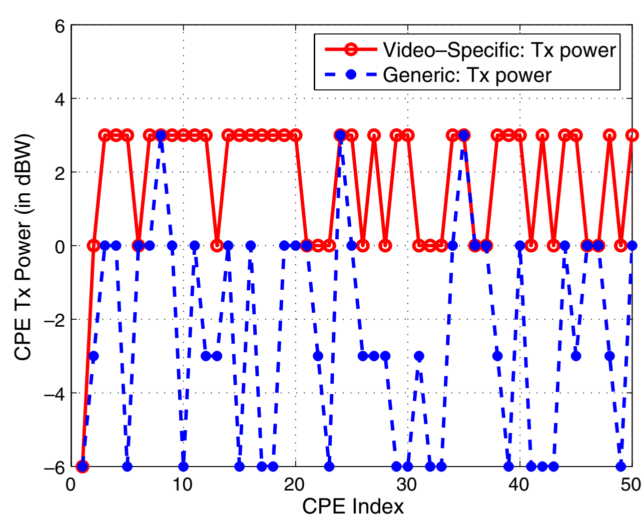


Fig. 16 Comparison of CPE transmit power when different utility functions are employed

Table 4 Performance comparison when using different utility functions (four channels available for use at BS)

	The video-specific utility function (10)	The generic utility function (5)
Average data rate	563 kbps	370 kbps
Average PER	2.0×10^{-4}	0.08
Average video distortion	1.26	137
Average CPE video utility	0.93	0.11
Average transmit power	2.05 dBW	−1.49 dBW

CE. Seemingly, WRAN BS achieves higher global utility when generic utility function is used. Intuitively, this result is attributed to the fact that less radio channels are actually allocated to CPEs and therefore higher WRAN BS spectrum utilization efficiency are achieved when adopting the generic utility function (as shown in Fig. 14). However, such plain comparison on global utility could be meaningless, since the definitions of CPE utility used in generic utility function and video-specific utility function are totally different. The difference in CPE utility definition also contributes to the difference of the achieved global utility.

Finally, in Fig. 16 we plot the equivalent isotropically radiated power (EIRP) from each CPE when four WRAN channels are available for use at BS. It can be seen that the transmit power is higher for most CPEs when the video-specific utility function is used. This indicates that the improvement in video utility achieved by the video-specific utility function is at the cost of higher transmission power at the CPEs. This is due to the fact that transmit power is included for optimization under the generic utility function, but not considered in the video-specific utility function. However, for some radio device (such as CPEs in IEEE 802.22 WRAN systems, which usually have AC power supply), the increased power consumption might not be a limiting factor. For battery-powered mobile subscribers, a trade-off comes into play among

(a) Generic utility function, best case
(b) Generic utility function, average case
(c) Generic utility function, worst case
(d)Video-specific utility function, best case
(e) Video-specific utility function, average case
(f) Video-specific utility function, worst case

Fig. 17 Visualization of decoded video frames at selected CPEs when different utility functions are used transmission power, video bit rate (bandwidth), and video distortion.

The above comparisons under four available WRAN channels at BS are summarized in Table 4. To further demonstrate the visual effect, we plot Frame 68 of the decoded video, when the two utility functions are used. Specifically, we show the worst, average, and best cases among all the CPEs for the experiments with each utility function. The visual difference in the quality of the decoded frames is obvious. In addition, the difference between Fig. 17d and Fig. 17f are quite small. This indicates that all the CPEs receive comparable video quality when the video-specific utility function is used, i.e., better fairness among the CPEs.

5 Related work

The concept of utility was initially introduced in economics, which is a generalized term for the satisfaction obtained by an individual from the "use" of a product or a service measured by the price that the individual is willing to pay [23]. In context of CR networks, utility is an assignment of values (numbers) to the current operating state such that the closer the cognitive radio comes to satisfying some goal, the greater the value assigned to the operating state [6]. Utility functions can incorporate a number of performance metrics and are usually dynamic and application-specific. Defining proper utility functions for wireless video networks is a very challenging and complicated issue, evidenced by the fact that disparate ways have been used to measure the utility of streaming video (for more details, see [23] and the references therein). It is also pointed out in [31] that "how a utility function should be exactly defined remains an open research issue. The choice can really depend on a number of factors (e.g., encoding and transmission algorithms) and, mainly, the design objective of the system." In [33], the authors reviewed some of the recent advances in cross-layer design schemes, which aim at providing significant gains in performance for video streaming systems through content-aware resource allocation. Advances in real-time video streaming (where the video is encoded and transmitted in real-time) as well as on-demand video streaming (where the video is pre-encoded in a media server) are discussed. It shows that the eventual success of video streaming over wireless networks depends on the efficient management of the limited system resources while taking into account the time-varying wireless channel conditions as well as the varying multimedia source content [33].

Partially due to the lack of creditable simulation tools for cognitive radio networks, testbed is usually developed to evaluate/validate various signal processing techniques and CE algorithms or protocols in CR networks. Quite a few CR testbeds of various levels of cognition capability have been developed and reported in recent years [24–28]. In addition, several CR testbeds (prototype or early-stage product) have been demonstrated at international conferences such as IEEE DySPAN 2008 and the 2008 Software Defined Radio Forum Technical Conference and Product Exposition, featuring dynamic spectrum access, cognitive radio device utilizing TV white space, network interoperability, and policy-based systems.

Video over wireless networks has become a very active research area attracting considerable efforts from the research community. Cross-layer optimization is an effective and important technique for providing satisfactory video quality in both infrastructure-based wireless networks [29, 30] and multi-hop wireless networks [13, 14, 22, 32], where the received video distortion is minimized by jointly considering parameters/mechanisms in multiple layers. The main difference between this paper and the existing work is that unlike in the prior work where the spectrum is exclusively used by the video sessions, we have to consider the presence and protection of primary users in the context of CR networks, which makes the problem more interesting and challenging.

6 Concluding remarks

Wireless video communication is one of the killer applications for emerging next-generation networks. As it is spectrum-hungry and distortion sensitive, intelligent and efficient radio resource management is critical to meet the demanding performance requirements and comply with spectrum policy as well. This paper investigates the impact of utility function selection on the performance of streaming video in CR networks. Two different utility functions have been adopted at a CE testbed designed for IEEE 802.22 WRAN BS. Our experiment results show that the received video quality at the CPEs can be significantly improved when a dynamic, content-aware, video-specific utility function is used as compared to the case when a static, predefined, generic utility function is used. The experiment results also show that the improved video quality is achieved at the cost of using higher transmit power (i.e., more power consumption) and occupying more radio channels (i.e., lower spectral efficiency). Although the 802.22 WRAN was used as an example system in this study, we conjecture that the utility function selection method and the general conclusions are applicable to streaming video applications in other types of cognitive wireless networks as well.

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References

1. Reed J (2002) Software radio—a modern approach to radio engineering. Prentice Hall: Upper Saddle River
2. FCC (2003) Facilitating opportunities for flexible, efficient, and reliable spectrum use employing cognitive radio technologies. Notice of Proposed Rule Making and Order, FCC 03–322
3. Akyildiz I, Lee W, Vuran M, Mohanty S (2006) Next generation/dynamic spectrum access/cognitive radio wireless networks: a survey. Elsevier Computer Networks 50(13): 2127–2159
4. Zhao Q, Sadler B (2007) A survey of dynamic spectrum access—Signal processing, networking, and regulatory policy. IEEE Signal Processing 24(3):79–89
5. IEEE (2007) Draft standard for wireless regional area networks Part 22: cognitive wireless RAN medium access control (MAC) and physical layer (PHY) specifications: policies and procedures for operation in the TV bands. IEEE P802.22 Draft Standard (D0.3)
6. Zhao Y, Mao S, Neel J, Reed J H (2009) Performance evaluation of cognitive radios: metrics, utility functions and methodologies. Proc IEEE 97(4):642–659
7. Peha JM (2009) Sharing spectrum through spectrum policy reform and cognitive radio. Proc IEEE 97(4):708–719
8. Gaeddert J, Morales L, Zhao Y, Bae K, Reed J (2007) Cognitive engine design for 802.22 WRAN base stations. Blacksburg, VA, June 2007, poster presented at the Wireless@Virginia Tech 2007 Wireless Personal Communications Symposium
9. Zhao Y, Gaeddert J, Morales L, Bae K, Reed J (2007) Development of radio environment map enabled case- and knowledge-based learning algorithms for IEEE 802.22 WRAN cognitive engines. In: Proc. the 2nd international conference on cognitive radio oriented wireless networks and communications (CROWNCOM 2007), Orlando, pp 44–49
10. Zhao Y, Morales L, Gaeddert J, Bae K, Um J, Reed J (2007) Applying radio environment map to cognitive wireless regional area networks. In: Proc. the 2nd IEEE international symposium on dynamic spectrum access networks (DySPAN 2007), Dublin, pp 115–118
11. Stulmuller K, Farberand N, Link M, Girod B (2000) Analysis of video transmission over lossy channels. IEEE J Sel Areas Commun 18(6):1012–1032
12. Wang Y, Wu Z, Boyce J (2006) Modeling of transmission-loss-induced distortion in decoded video. IEEE Trans Circuits Syst Video Technol 16(6):716–732
13. Kompella S, Mao S, Hou Y, Sherali H (2007) Cross-layer optimized multipath routing for video communications in wireless networks. IEEE J Sel Areas Commun 25(4): 831–840
14. Kompella S, Mao S, Hou Y, Sherali H (2009) On path selection and rate allocation for video in wireless mesh networks. IEEE Trans Networking 17(1):212–224
15. Corderio C, Challapali K, Birru D, SSN (2005) IEEE 802.22: the first worldwide wireless standard based on cognitive radios. In: Proc. the 1st IEEE international symposium on new frontiers in dynamic spectr-um access network (DySPAN 2005), Baltimore, pp 328–337
16. Zhao Y, Reed J, Mao S, Bae K (2006) Overhead analysis for REM-enabled CR networks. In: Proc. the 1st IEEE workshop on networking technologies for software defined radio networks, Reston,pp 18–25
17. Zhao Y, Le B, Reed J (2006) Network support—the radio environment map. In: Fette B (Ed) Cognitive radio technology, ch 11. Elsevier, Amsterdam, pp 337–363
18. Blum C, Roli A (2003) Metaheuristics in combinatorial optimization: overview and conceptual comparison. ACM Comput Surveys 35(3):268–308
19. Chiang T, Zhang Y (1997) A new rate control scheme using quadratic rate distortion model. IEEE Trans Circuits Syst Video Technol 7(1):287–311
20. Ma S, Gao W, Lu Y (2005) Rate-distortion analysis for H.264/AVC video coding and its application to rate control. IEEE Trans Circuits Syst Video Technol 15(12):1533–1544
21. He Z, Mitra S (2002) A linear source model and a unified rate control algorithm for DCT video coding. IEEE Trans Circuits Syst Video Technol 12(11):970–982
22. Wu D, Ci S, Wang H (2007) Cross-layer optimization for video summary transmission over wireless networks. IEEE J Sel Areas Commun 25(4):841–850
23. Wikstrand G, Sun J (2004) Determining utility functions for streaming low bit rate soccer video. Department of Computing Science, Umea University, Tech Rep
24. Sokolowski C, Petrova M, de Baynast A, Mahonen P (2008) Cognitive radio testbed: exploiting limited feedback in tomorrow's wireless communication networks. In: Proc. IEEE ICC'08 communications workshops, Beijing, pp 493–498
25. Park J, Kim K, Song T, Lee S, Hur J, Lim K, Laskar J (2008) A cross-layer cognitive radio testbed for the evaluation of spectrum sensing receiver and interference analysis. In: Proc. IEEE CrownCom'08, Singapore, pp 1–6
26. Rieser C, Rondeau T, Bostian C, Gallagher T (2004) Cognitive radio testbed: Further details and testing of a distributed genetic algorithm based cognitive engine for programmable radios. In: Proc. IEEE MILCOM'04, Monterey, pp 1437–1443
27. Mishra S (2005) A real time cognitive radio testbed for physical and link layer experiments. In: Proc. IEEE DySPAN'05, Baltimore, pp 562–567
28. McHenry M, Livsics E, Nguyen T, Majumdar N (2007) XG dynamic spectrum access field test results. IEEE Commun 45(6):51–57
29. van der Schaar M, Krishnamachari S, Choi S, Xu X (2003) Adaptive cross-layer protection strategies for robust scalable video transmission over 802.11 WLANs. IEEE J Sel Areas Commun 21(10):1752–1763

30. Deb S, Jaiswal S, Nagaraj K (2008) Real-time video multicast in WiMAX networks. In: Proc. IEEE INFOCOM'08, Phoenix, pp 1579–1587
31. Cotroneo D, Paolillo G, Pirro C, Russo S (2005) A user-driven adaptation strategy for mobile video streaming applications. In: Proc. 25th IEEE international conference on distributed computing systems workshops. Columbus, pp 338–344
32. Wei W, Zakhor A (2007) Multiple tree video multicast over wireless ad hoc networks. IEEE Trans Circuits Syst Video Technol 17(1):2–15
33. Pahalawatta PV, Katsaggelos AK (2007) Review of content-aware resource allocation schemes for video streaming over wireless networks. Wirel Commun Mob Comput 7(2): 131–142

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