IOSR Journal of Electronics and Communication Engineering (IOSR-JECE)
e-ISSN: 2278-2834,p- ISSN: 2278-8735.Volume 18, Issue 6, Ser. I (Nov. – Dec. 2023), PP 30-36
www.iosrjournals.org

Improved Metaheuristic Approach For User Capacity Analysis Of A Television White Space Network

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Abstract

Television White Space (TVWS) is the underutilized or unused radio frequency spectrum that was originally allotted for television broadcasting. It has enormous potential to increase internet access, especially in places where traditional connectivity choices are scarce. TVWS's capacity to pass through barriers and resilience to attenuation and fading has drawn attention to its potential to offer wireless broadband connectivity, especially in underdeveloped areas. But in order for it to be implemented successfully, operational, technological, and regulatory issues must be carefully considered. When used properly, TVWS can be a useful instrument in the fight against the digital divide and to advance equitable access to information and services. A deployed network must be carefully planned in order to deliver the required coverage and the desired quality of service. In this study, the distance distribution approach was used to model, and MATLAB simulation was used to analyse user capacity. According to the findings, a network with one base station and ten customer premises equipment (CPE) could support 2.1 Mbps of users with a signal quality of only 10dB. a better result than studies conducted in a similar environment in the African region.

Keywords: *Customer premises equipment, Distance distribution, Television white space, User capacity.*

Date of Submission: 21-12-2023 Date of Acceptance: 31-12-2023

I. Introduction

During the global pandemic era, limited mobility and in-person interactions led to the rise in popularity of broadband network connectivity in rural areas. This was because it became the primary method of communicating with friends and family, exchanging goods and services, and completing tasks related to education, health, science, security, and media, among other things. Lack of internet connectivity in rural areas limits economic processes and restricts the flow of knowledge to the general public, contributing to the troubling phenomenon known as the "digital divide" in these times [1]. Television White Space Technology (TVWST) will enable the development of effective and long-lasting rural communities' access to broadband.

The usage of Television White Spaces for communications systems is one alternative method of spectrum utilization that is becoming more and more common worldwide. "portions of spectrum kept unoccupied for broadcasting, are often referred as looped spectrum" is what TV white spaces, or TVWS, are. Due to their exceptional propagation properties, TV White spaces are quite popular for wireless communications globally. Guidelines governing the use of TV white spaces for wireless connectivity (both fixed and mobile) have previously been developed in several countries. Television white spaces generally are frequencies belonging to the Very High Frequency / Ultra High Frequency (VHF/UHF) range that are unoccupied, underutilized, or interspersed within television broadcasting channels. (within 470 MHz to 694) [2]. The advantage of propagating at a reduced frequency is that reduced frequencies go farther and pass through walls more effectively because of their long wavelength lower frequency can diffract over obstacles like mountains ranges and travel beyond the horizon, following the contour of the earth. However, the flaw is a capacity problem. As it spreads, it does not carry many users.

A priceless technological system called TV white space has the potential to promote the growth of ICT connectivity in Africa. When TV white space connectivity is attained in the majority of African nations, it might increase the complete broadband internet connection accessibility in some village and urban areas of Africa. As broadband usage increases, the digital divide will be less difficult to close [3].

II. Literature Review

At each particular location, TVWS can manifest itself in a variety of ways. The amount of spectrum that is available for TVWS can differ greatly depending on a number of factors, such as geographic characteristics, the degree to which the incumbent TV broadcasting service could be interfered with, Objectives for Television coverage, associated planning, and TV channel usage. TVWS accessibility can be broadly classified into [4]:

1. **Space:** Geographical regions where there is currently no broadcast signal since it is outside the existing TV coverage range. Additionally, those areas with intentional physical separation between sites that use the same TV channels.
2. **Time domain:** The TVWS could become accessible while a broadcasting emitter is offline if the authorized broadcasting broadcaster isn't using the assigned frequency channel within a predefined period of time. This allows the channel to become utilized as a TVWS without causing interference.
3. **Frequency:** Some geographical areas see empty channels in a TV band design as a result of interference avoidance strategies such using guard bands.
4. **Height:** Height reflects the accessibility of TVWS at a particular location as a result of the TVWS transmission site's height and antenna height with respect to the neighbouring TV broadcasting coverage reception.

TV White Space Technical Overview

The cognitive radio-based architecture serves as the foundation for the TVWS technology-based communication system. A cognitive radio system (CRS) is a radio system that uses technology to learn about its internal state, established policies, and operational and geographic environment. It then uses this knowledge to dynamically and autonomously modify its operational parameters and protocols in order to accomplish predetermined goals. Geolocation/Database, Spectrum Sensing, and Combined Spectrum Sensing and Geolocation/Database are the main-enabling technologies [4].

- **Geolocation/Database:** In order to find out which frequencies they can utilize at a given area, cognitive devices measure their position and look up information in a "geo-location" database. Important parameters are the frequency of database and the accuracy of the location. Unless the devices have correctly determined what channels, if any, are accessible in their current location through the information stored in the database, they are not permitted to communicate. This necessitates using a channel set aside for this purpose or using another method to gain first access to the database. Since exact information for the requested location cannot be obtained from the information stored in the database unless the position of the CRS node is known, geolocation is a crucial component of the database access technique.
- **Spectrum Sensing:** Devices use spectrum sensing to search through all of the possible channels for the presence of protected services. The process of spectrum sensing basically entails measuring something inside a candidate channel to see if any protected services are present. Sensing may be used on neighbouring channels if a channel is found to be empty to ascertain any potential transmission power limitations.
- **Combined Spectrum Sensing and Geolocation/Database:** The steps involved in using a combined approach are: device location, figuring out the effective isotropic radiated power (EIRP) and the useful frequencies. Verify whether there are any acceptable frequencies available and enable transmission.

III. Materials and Method

The distance distribution method with density (λ) 0.1 was utilized in this paper to analyse the capacity of a connected user for Customer Premise Equipment (CPEs) within channel arrangement. MATLAB was employed for this analysis. One remote white space base station (WSBS) is used in the design to service several customer premise equipment (CPEs). A cell is made up of White Space Base Station and its collection of CPEs. TVWS penetration power and capacity must be maximized by designing the optimum spacing for co-channel CPE separation. The Parameters of materials used for analysis: CPE Separation, The WSBS EIRP as well as CPE EIRP, the number of CPEs each WSBS, the CPE separation from the WSBS, and the Signal to Interference and Noise Ratio (SINR).

TV White Space Design Model

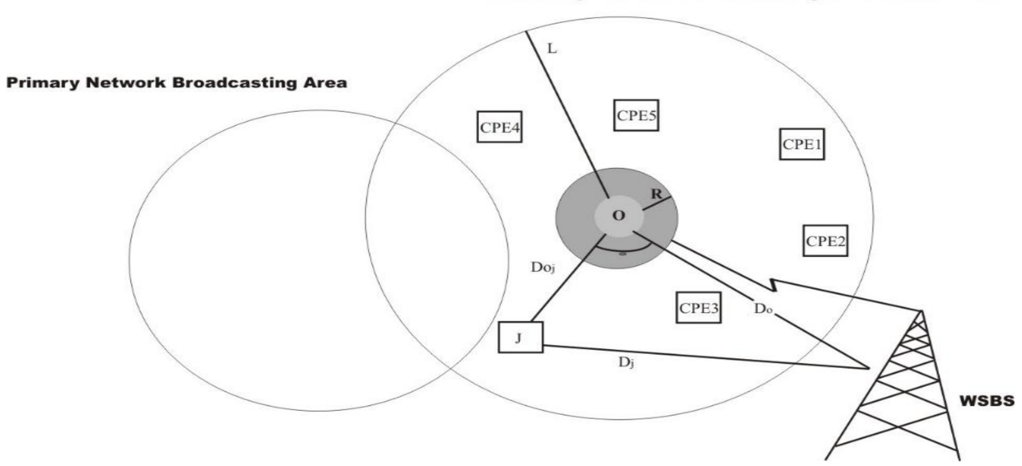


Fig. 1: Primary-secondary systems coexistence design model [5]

This example demonstrates the TVWS user-focused deployment methodology, in which deployment is expected to occur randomly [6]. Poisson Point Process (PPP) with a density of 0.1 is used to distribute customer-premise equipment (CPE). The location of the base station is random in heterogeneous networks, where multiple small cell base stations might be installed. Fig. 2 presents a theoretical picture of the way 802.11n Wi-Fi routers provide customers with a final service (last-mile delivery). In contrast to existing Wi-Fi protocols, 802.11n runs in the 2.4 GHz and 5 GHz bands and offers multi-channel use. This wireless networking standard has a maximum data throughput of 600 Mbps and is backwards compliant with the 802.11a, b, and g protocols [7]. Furthermore, it makes MIMO possible, which improves the signal in the event that last-mile service needs to be expanded.

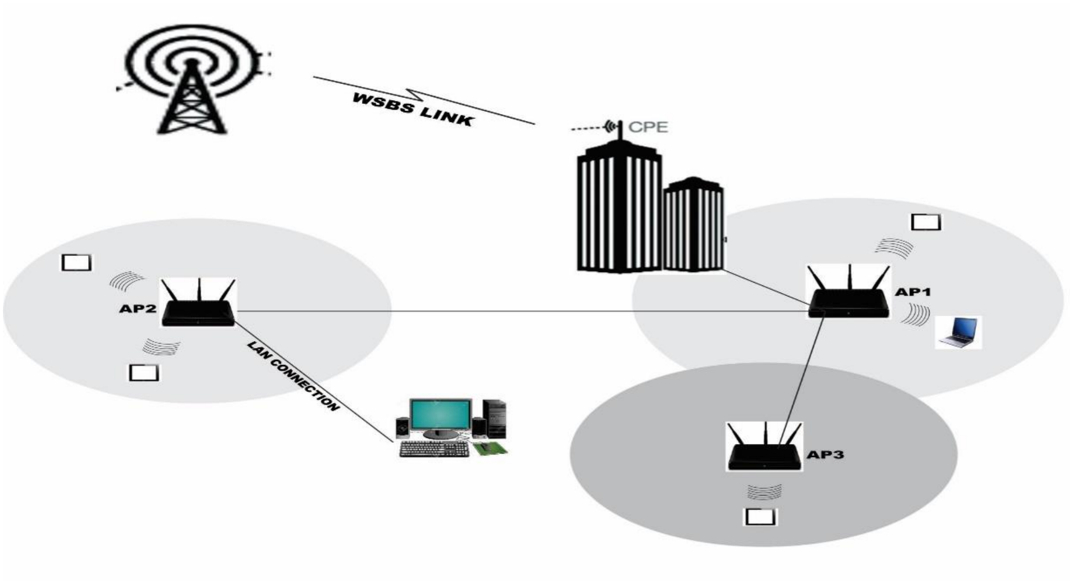


Fig. 2: Last Mile Network Access Architecture

The Shannon capacity for a specific target CPE ($CPEo$) at the center of a cluster C_o for a channel with bandwidth B_O. is stated as

$$C_o = B_O log_2(1 + SINR_o) \tag{1}$$

Where $SINR_o$ is the ratio of the received signal power (P_R) to the interference (I_{CPEo}) and Noise (N_o) at the centre CPE ($CPEo$) which is given as

$$SINR_o = \frac{P_R}{N_o + I_{CPEo}} \tag{2}$$

Let $P_{o,x}$ = interference power level of the xth CPE and
$L_{o,x}$= channel pathloss between $CPEo$ and xth CPE positioned at a distance $M_{o,x}$
Total interference at the centre CPE ($CPEo$) equals

$$I_{CPEo} = \sum_{x=1}^{N} I_{CPEx} + \tau_o \quad (3)$$

$$I_{CPEo} = \sum_{x=1}^{N} \frac{P_{o,x}(g_{o,x})^2}{L_{o,x}} + \tau_o \quad (4)$$

$$I_{CPEo} = \sum_{x=1}^{N} I_{CPEx} + \tau_o = \sum_{x=1}^{N} \frac{P_{o,x}(g_{o,x})^2}{L_{o,x}} + \tau_o \quad (5)$$

Where:
τ_o= self interference effect in $CPEo$
N = number of interfering CPEs in the cluster
$g_{o,x}$= gain between the CPEs
Permitting all CPEs to be configured identically for each CPE cluster, meaning:

$$p_{o,x} = p_o \ \ and \ g_{o,x} = g_{x,o} = g_o \quad (6)$$

Due to the fact that the base station's signal suffered from environmental deterioration before arriving, we can have that;

$$P_R = \frac{P_W g_W g_O}{L(M_O)} \quad (7)$$

Where:
P_W= power gain from the WSBS (white space base station)
g_W= channel gain from the WSBS
$L(M_O)$ = Path loss between whitespace base station and $CPEo$ which depend on the distance between them M_O.
If we combine (2), (5) and (7) to get another $SINR_o$ as:

$$SINR_O = \frac{\frac{P_W g_W g_O}{L(M_O)}}{N_o + \frac{P_{O,x}(g_{O,x})^2}{L_{O,x}}} \quad (8)$$

Replacing $g_{o,x}$ and $P_{o,x}$ respective with g_o and P_o

$$SINR_O = \frac{P_W g_W g_O}{L(M_O)[N_O + \sum_{x=1}^{N} \frac{P_{O,x}(g_{O,x})^2}{L_{O,x}}]} \quad (9)$$

To fully benefit from the white space network, maintaining high signal strength (SINR) is necessary for a wider coverage area.

The approach used is the distance distribution method since TV white space is widely available. Here a two-dimensional plane point with its nth are provided as [8]:

$$F_n(r) = \frac{e^{(-\lambda \pi r^2)^n}}{r\,\Gamma(n)} \quad (10)$$

Where:
$\Gamma(n)$ is an incomplete gamma function and λ is the number of nodes per surface area.

However, we must aim for a specific received signal power in relation to the noise and interference SINR (γ_T) to be satisfied.

The following represents the likelihood that the signal power will decrease less than the desired amount.

$$P_{out} = P_r(SINR_o \le \gamma_T) \quad (11)$$

From (9), assuming a very tiny drop noise level N_O, allows us to input γ_T as follows.

$$\boldsymbol{\gamma_T} = \frac{\boldsymbol{P_W g_W g_O}}{\boldsymbol{L(M_O)[\sum_{x=1}^{N} \frac{P_O(g_O)^2}{L_{O,x}}]}} \quad (12)$$

Note: the distance between the CPEo and M CPE from (12) will be as follows when equal distance interference nodes $M_{o,x}$ are used.

$$P_W g_W g_o = \frac{\gamma_T L(M_O) N P_O (g_O)^2}{L(M_{O,x})} \quad (13)$$

$$M_{o,x} = M_o = \frac{\gamma_T L(M_O) N P_O g_O}{P_W g_W L} \quad (14)$$

From cumulative distribution function (10) within a cluster of CPE the probability outage (P_{out}) of a link to the closest CPE is taken as:

$$P_{out} \simeq 1 - e^{(-\lambda \pi r M^2)} \sum_{k=1}^{n=1} \frac{(\lambda \pi M^2)^k}{k!} \quad (15)$$

As a result, the total capacity $C_o$of CPEo is given by (11) when a certain targeted area has v available channels.

$$C_o = \sum_{k=1}^{V} (1 - P_{out}) B_k \, log_2(1 + \gamma_T) \quad (16)$$

Our link capacity becomes:

$$\mathrm{C_o} \simeq \sum_{k=1}^{V} \sum_{q=1}^{N-1} \mathrm{B_k} \log_2(1 + \gamma_T) \frac{(\lambda \pi M^2)^q}{q!} e^{(-\lambda \pi M^2)} \quad (17)$$

Three radio antennas in white space separated by 120 degrees are employed by the base station in this study to provide omnidirectional coverage of the region. Three sectors, or the 120 degrees of coverage that each antenna offers, make up a cell, which is the area that an on-base station covers geographically.

In the event that a cell has N sectors, C_P is its capacity, and C_e is the total capacity for all sectors, then;

$$C_P = \sum_{I=1}^{S_N} C_e \qquad (18)$$

Assume that, for a given channel bandwidth B_S, every sector has an equal capacity to cover. Equation (18) yields the capacity of each customer-premise equipment (CPE) as follows.

$$C_N \simeq \frac{1}{S_N}\sum_{1}^{S_N}\sum_{q=1}^{N} B_s log_2(1+\gamma_T)\frac{(\leftthreetimes\pi M^2)^q}{q!}e^{(-\leftthreetimes\pi M^2)} \qquad (19)$$

Each user's capacity on a CPE is determined by the number of users requesting the service as well as the capacity of the CPE channel. The CPEs' capacity limits the maximum throughput that an end user may attain, as individual users are linked through Wi-Fi access points in white space has a bandwidth bigger than the CPEs. The effect of Wi-Fi AP interference on end-user throughput is not taken into account in this study. The user's capacity may change based on how far away they are from the AP because of variations in the quality of the signal they receive. Not every user will be present in every node at all times. Given an oversubscription ratio of ψ:1, the following is the number of users for each cell.

$$N_u = \frac{\Psi C_P}{C_N} \qquad (20)$$

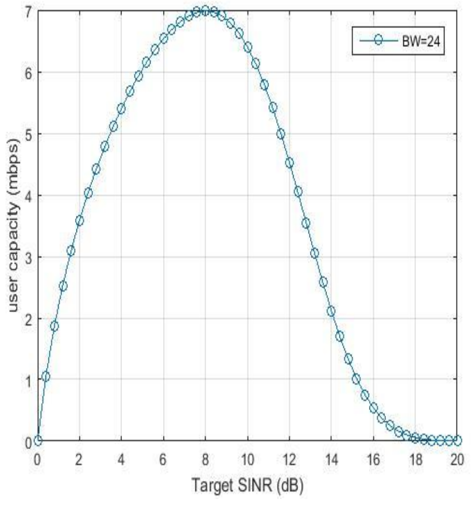
Utilizing channel aggregation, capacity per user can be significantly increased at the last mile due to the abundance of channels available in rural locations. The majority of the time, a channel bandwidth of up to 24 MHz can be obtained by combining up to three 8 MHz channels.

IV. Results and Discussion

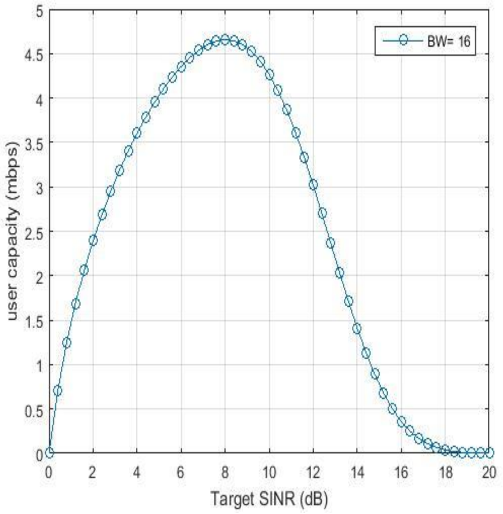
The goal of the paper is to evaluate the TVWS network's channel capacity in relation to various network factors. The NCC guidelines that have been established served as the foundation for the analysis. Table 4.1 gives the parameters used for this research work. The research used ⋋ = 0.1 which means one CPE for a 10km square area (which gives us 1.8km radius)

Table 1: Parameters for Simulation

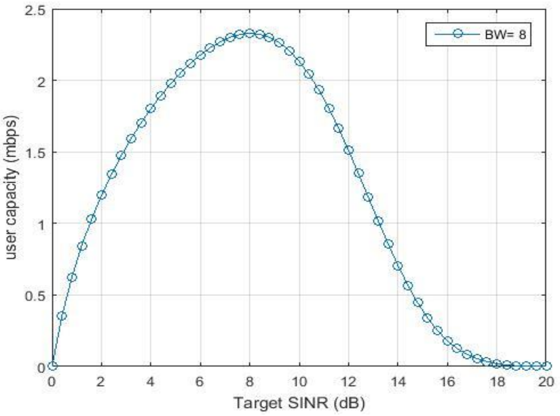
S/N	PARAMETERS	Symbols	VALUES
1	Channel bandwidth	B_s	8MHZ
2	Gain of the WSBS	g_w	11DB
3	WSBS EIRP	P_W	36 DBM
4	CPE EIRP	g_o	30DBM
5	WSBS HAAT	H_B	60M
6	CPE HAAT	H_{re}	10M
7	Noise	N	-174 BM
8	CPE Density	⋋	0.1



(a)



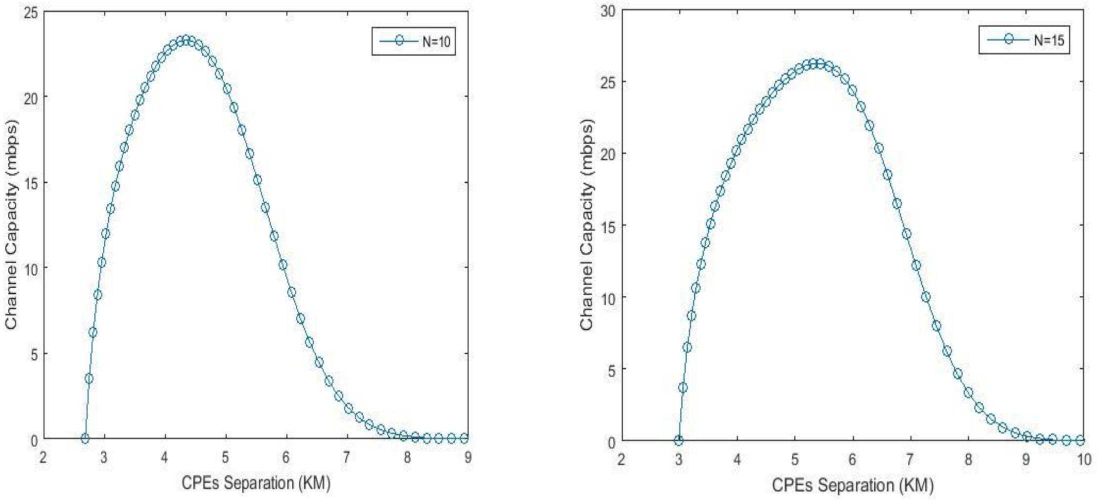
(b)



(c)

Fig. 3: Capacity per user for different channel aggregation for Do = 5 km

Fig. 3 shows how channel aggregation affects user capacity. As the channel capacity doubles, so does the user capacity. For example, with one-level aggregation, the capacity per user increases from around 2.1 Mbps - 4.2 Mbps at a SINR of 10 dB. At the same desired SINR, aggregating three channels yields a user capacity of about 6.4 Mbps. Channel aggregation is typically restricted to three carriers due to contiguous channel availability issues and limited system power. Adding non-contiguous or inter-band channels to a single band would increase hardware complexity and expense. Once more, the increase in user capacity is clearly greater than the one seen in [9][10], whereby an average capacity of about 4 Mbps was achieved by using one channel each CPE.



(a) (b)

Fig. 4: Capacity vs CPE separation for SINRt = 10 dB and o D = 5km

The capacity per user is one of the key performance metrics for wireless networks. It illustrates how the separation of CPEs will affect the capacity per user. The channel capacity as well as the capacity per user in this scenario behaves intuitively similarly. However, although the pattern holds true for varying target SINR, when the number of nodes in the network is taken into account, it varies. Figure 4 illustrates how the capacity per user falls at the rise with N. This suggests that when there are fewer users in the network, the capacity per user is higher. But as can be expected, the small user base leads to underuse of the channel, which prevents it from reaching its anticipated capacity. The ideal distance between CPEs for a specific goal SINR is also displayed in Fig. 4. It is evident that when N rises, the ideal distance between CPEs can also rise, potentially leading to an increase in maximum user capacity to offset the extra interference. D is dependent on additional parameters, as demonstrated in Figure 4, it can be derived in this instance by changing one of the factors while maintaining the rest constant.

V. Conclusion

The overall goal of this work was to analyse the TVWS network's radio network performance when it was implemented in a channel environment with the Hata propagation model in place of a distance CPE distribution. The study made use of the space between CPE in largely inhabited areas to cover a great number of potential customers while achieving the highest capacity. The capacity analysis methodology for the TVWS network, which is appropriate for areas of low population density, has been established in this study and is deployed based on the distance distribution approach. While maximizing the use of the available spectrum and power, a sizable number of sparsely scattered consumers can be served. The study took into account uniform device designs and a scenario with CPEs positioned equally apart. Real-world implementation, however, is probably going to include different circumstances. The user capacity of almost 2.2 Mbps was attained with a WSBS range of five kilometres and an expected SINR of only 10 dB, and bandwidth of 10MHz demonstrating the clear impact of CPE spacing on user capacity. It is anticipated that the real TCP throughput will be marginally greater since error control and upper layer overheads will be reduced. It is recommended that more research be done on TCP capacity and how last-mile Wi-Fi extensions affect user throughput and CPE performance, taking into account various CPE settings.

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