[[1]](#footnote-1)

Throughput-oriented Caching and Power Allocation Algorithm Based on Convex Optimization for B5G Wireless-Optical Broadband Access Network

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# INTRODUCTION

T

HE promotion of the Beyond 5th Generation (B5G) networks is imperative, motivated by the numerous emerging applications such as autonomous vehicles and telemedicine. In the upcoming scenario of B5G, hundreds of millions of terminals will be deployed densely around the world, and the global Internet trafﬁc will increase nearly threefold over the next 5 years, according to Cisco [1]. Therefore, higher requirements would be put on the access networks in the aspects of transmission range, bandwidth capacity and energy consumption. The hybrid Wireless-Optical Broadband Access Network (WOBAN), which can benefit not only from the long transmission distance of optical fiber but also the flexibility of wireless technology, is considered to be the most capable candidate of B5G accessing and has already been widely deployed. However, WOBAN still suffers from the bottleneck of the capacity in its wireless access domain due to the power limitation, which prevents the volume of access devices and the end-to-end transmission rates from further upgrade. Accordingly, a core issue is to improve the throughput of WOBAN, e.g. the total channel capacity obtained by the wireless access devices.

The optimization of throughput in wireless access networks has already attracted a great deal of research interest. The authors in [2] develop a both centralized and distributed antenna transmission system that uses intermediate-frequency-over-fiber (IFoF) technology to promote throughput. In [3], a new network architecture is designed for the cooperative transmissions scenario where the modulation problem is analyzed. Due to the limited wireless channel state, a joint power category and bandwidth allocation schemes with the aim of maximizing the delivered ﬁle amount is proposed in [4]. The authors in [5] provide the condition when energy efﬁciency can beneﬁt from caching with 2 × 2 multiple-input multiple-output (MIMO) configuration.

However, the influence of the optical fiber transmission on wireless domain has not been paid much attention in the above studies. By considering the limitation brought by the capacity of feeder fiber as a constraint, the authors in [2] mathematically formulate the throughput optimization problem and solve it. Nevertheless, it bluntly considers file size as constant, which reduced system flexibility and is not in line with the network slicing ideas of B5G network. In addition, the state-of-the-art caching mechanism of WOBAN is not fully utilized in giving more impressive achievements. By analyzing the probability distributions, the popularity of the files to be cached should be traceable and a caching selection strategy is preferred to achieve a more rational use of the limited power resource.

In this paper, driven by the overall mission of maximizing network throughput, we mathematically formulate the optimization issue with power and capacity constraints in B5G WOBAN. The solving process is conducted by three steps of research. Firstly, by learning the receiving preferences of user equipment (UE), a decision algorithm is proposed to determine whether a certain file should be cached, namely cache file selection strategy (CFSS). Secondly, we proved that given CFSS, the problem is convex and can be mapped into a multi-choice knapsack problem (MCKP) with other treated constraints from optical domain. Finally, we solved the MCKP problem and thereby proposed a novel dynamic algorithm as a synthesis design for caching selection and power allocation. Considering the complex characteristics in the scenario of B5G, the proposed algorithm gives a rather wide choice of input parameters. Experiments show that the proposed algorithm is nb than what traditional schemes on what parameters.

The main contributions of our work are summarized as follows.

1)From a more holistic perspective, the proposed algorithm takes into account the influence of optical fiber transmission domain during the optimization of wireless throughput. This promotes to achieve the global optimal solution of WOBAN system in the true sense.

2) The unique caching mechanism of WOBAN is well utilized. By selecting the cache file following probability distribution, we make a more efficient use of the limited power resources so that the consumption is supervised to make greater contributions to the improvement of network throughput.

3) The convex problem has the characteristic that the local optimal solution is equal to the global optimal solution. By adding constraints, the MIP problem is transformed into a convex problem. Therefore, the computational complexity of the proposed algorithm is greatly reduced, which is not only suitable for processing larger data sets, but also helps reduce latency in B5G scenarios

The rest of this paper is organized as follows. We ﬁrst introduce the system model in Section II. Then, in Section III, the joint cache selection and power allocation optimization problem is formulated, and the transformation of the optimization problem into MCKP based on the proposed cache selection method is described. Simulation results are shown in Section IV and concluding remarks are provided in Section V.

# System Model

## Network Model

The architecture of the hybrid WOBAN considered in this paper is shown in Figure 1. In WOBAN, optical signal in the core network is issued by optical line terminal (OLT) through a passive optical network (PON) to different optical-network unit-base stations (ONU-BSs) [6]. As the interface of optical and wireless domains, each ONU-BS has three independent functions performed simultaneously. The first is caching mechanism. It means to store a certain number of files that may be requested by the UE in advance, which is designed to reduce the satisfaction delay on the UE side and to release the backhaul pressure of fibers. The second is the interaction mechanism with the core network. When the file requested by UE is not pre-cached, the ONU-BS requests and receives the file from the core network through fiber backhaul. The third is the interaction mechanism with UE. The ONU-BS performs photoelectric conversion and transmits wireless signals carrying different files to different UE under its jurisdiction.

As the edge of the core network, OLT transmits optical signals that need to be issued through the feeder fiber to an optical splitter. The split ratio of the optical splitter is usually 1:32 or 1:64, which means it governs certain number of ONU-BSs located in different physical sites by the distribution fibers respectively.

The ONU-BSs are indexed by a set *N*= {1, 2, ···, *n*, ···, *N*}. In the coverage area of ONU-BS*n*, the set of UE associated with it is denoted by *Φn*. We index UE by an index set *J* = {1, 2, ···, *j*, ···, *J*}. We assume that all the ONU-BSs in system adopt orthogonal frequency-division multiple access (OFDMA) to transmit data, that is to say, each ONU-BS assigns wireless orthogonal subcarriers with different transmission power levels to different UE. For each sub-channel from *ONU-BSn* to *UEj*, the maximum bandwidth is denoted by *Pnj*, and the Rayleigh channel gain is denoted by *gnj*, which is assumed to follow the exponential distribution.

Accordingly, the receiving signal-to-interference-plus-noise ratio (SINR) obtained by the wireless access devices *UEj* via *ONU-BSn* can be expressed as

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| --- | --- |
|  | (1) |

where N02 represents the power of additive white Gaussian noise (AWGN).

According to Shannon Theory, the channel capacity of the wireless sub-channel from the wireless access devices *UEj* to *ONU-BSn* can be expressed as

|  |  |
| --- | --- |
|  | (2) |

where N\{n} means that all values in N are traversed except n, and all the UE under the jurisdiction of *ONU-BSn* is assumed to share the same spectrum bandwidth which is indicated by *W*.

In order to increase the channel capacity, it is necessary to achieve a global improvement on the reception SINR of every UE, according to (2). Ideally, we assume that the UEs connected to ONU-BSs distributed in different physical locations are farther away, that is, the inter-channel interference of the wireless signals between them is extremely small and can be ignored mathematically. Therefore, the highest channel rate received by *UEj* can be derived as

|  |  |
| --- | --- |
|  | (3) |

## Power Consumption Model at ONU-BSs

According to (3), it is obvious that with the given network topology, channel status and environmental noise, making *ONU-BSn* increase the wireless transmit power allocated to *UEj* can effectively increase the receiving channel capacity between them. Therefore, increasing the transmission power as well as optimizing its allocation mechanism at each ONU-BS can improve the overall channel capacity.

However, the transmission power cannot be increased without limitation. The restriction lays in the maximum power limit of ONU-BS and is ultimately reflected on the constraint of maximum capacity of the optical feeder fiber. More specifically, let denotes the total power consumed by *ONU-BSn*, so is divided into two parts for backhaul and delivering respectively. The part of power allocated for wireless signal transmission to *UEj* is denoted as , and the part allocated for caching files is denoted as . Nevertheless, the influence of hardware such as the consumption of the photoelectric converter should also be taken into account. For notational convenience, we assume that the remaining power consumption except for and , which is determined by the physical structure of the *ONU-BSn* itself, is omitted for it is a constant denoted by . Therefore, the total power consumption model of *ONU-BSn* can be established through the adjunction of caching power consumption in the typical wireless network power consumption model [11] as follows

|  |  |
| --- | --- |
|  | (4) |

where denotes the ratio of the power reserved for wireless transmission within *ONU-BSn* to the actual transmit power of the wireless signal issued to access devices through the wireless channel, in other words, a coefﬁcient that measures the impact of power ampliﬁer, power supply and cooling [12].

Obviously, we have the maximum power constraint as follows

|  |  |
| --- | --- |
|  | (5) |

where denotes the maximum power limit of *ONU-BSn* and depends on the circuit design in physical layer. In this paper, it is assumed that all the ONU-BSs comply with a same maximum power .

## Caching Model and Selection Strategy

According to (5), it can be inferred that even though increasing has proven to be an effective means to directly increase throughput, there is still a tradeoff laying between and at ONU-BS where power is constrained, which limits the proportion of wireless transmit power from violating the reasonable demand of caching power .

Caching power is for the storage of cache files that may be requested by UE. In the light of the energy-proportional model for caching power consumption in content-centric networking [13] [14], the consumption of caching power is proportional to the total number of bits cached at *ONU-BSn*. Let ω be a coefﬁcient reﬂecting the caching efﬁciency in watt/bit, which depends on the characteristic of the caching hardware. The caching power can be expressed as

|  |  |
| --- | --- |
|  | (6) |

where denotes the total number of bits cached by *ONU-BSn*. We consider the most commonly used caching device, high-speed solid state disk (SSD) as the caching hardware in the system. Therefore, the value of ω is constant to be 6.25×10−12 watt/bit. In this paper, we consider that all ONU-BSs are cache-enabled and the cache capacity of *ONU-BSn* is denoted by *Hn* (bits) (*n*∈N), then we have

|  |  |
| --- | --- |
|  | (7) |

During the application process of WOBAN, each UE request files from ONU-BS. If the ﬁle requested has been already cached by its associated ONU-BS, the UE can get the ﬁle directly from this ONU-BS. Otherwise, the ﬁle should be fetched from the core network via a capacity-limited ﬁber backhaul, which is assumed to be a PON consisting of the distribution fiber and the feeder fiber in this paper. The maximum capacity of the fiber backhaul is denoted as *C*. Accordingly, the amount of files that are not pre-cached cannot exceed the maximum capacity of fiber backhaul, which put requirements on the caching file selection strategy.

The requested ﬁles are indexed by a set *F* = {1, 2, ..., *f*, …, *F*}, which are stored as a ﬁle library at the remote ﬁle server in the core network. For ﬁle (k ∈F), its size is denoted by (bits). The probability that is requested by *UEj* is denoted as and remains to be configured in the ONU-BSs, where we have

|  |  |
| --- | --- |
|  | (8) |

to denote the probability that is requested, namely the file popularity. Obviously, ONU-BS is bound to prefer those files with higher file popularity to have the priority to be cached. The cache decision on the at *ONU-BSn* is denoted as . More specifically, means that *ONU-BSn* is going to cache the file and vice versa. Accordingly, the cache selection strategy is to find out the value of for each n and k.

From the perspective of UE, let

|  |  |
| --- | --- |
|  | (9) |

denotes the probability that ﬁles requested by UE are already cached at *ONU-BSn* (i.e., cache hit ratio), and denote the probability that ﬁles requested by UEs are not cached at *ONU-BSn* (i.e., cache miss ratio), where we have

|  |  |
| --- | --- |
|  | (10) |

With the cache miss ratio at *ONU-BSn*, the average ﬁber backhaul bandwidth occupied by *UEj* at *ONU-BSn* can be written as

|  |  |
| --- | --- |
|  | (11) |

Therefore, the backhaul constraint of all J UE should be satisﬁed as

|  |  |
| --- | --- |
|  | (12) |

Taking into account the guarantee of the Quality of Service (QoS) for each UE device, we define the lowest tolerable transmission rate of *UEj* as . Therefore, the constraint of transmission rate brought by UE can be expressed as

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| --- | --- |
|  | (13) |

# Problem Statement

In this section, we ﬁrst mathematically formulate the throughput optimization problem where power allocation and fiber backhaul capacity are jointly considered. Then, we decompose the problem into two sub problems, i.e., transmit power allocation problem related to power control and cache file selection problem related to user association and ﬁle placement. By relaxing the non-convex Mixed Integer Programming (MIP) problem to a convex one with the tight approximation, the throughput optimization problem is converted to a form that can be handled by MCKP.

## Formulation of Throughput Optimization Problem

To represent the tradeoff relationship between ﬁle delivery delay and power consumption, a weighted sum utility function is used. Then, we can formulate the throughput optimization problem as a utility maximization problem. This method is widely used in multi objective problem optimization, for example, in [41], [42]. By jointly considering power allocation and fiber backhaul capacity, the throughput optimization problem is formulated as a mixed-integer programming (MIP) expressed as follows.

P1:

|  |  |
| --- | --- |
|  | (14a) |

s.t.

|  |  |  |
| --- | --- | --- |
|  | | (14b) |
|  | (14c) | |
|  | | (14d) |
|  | (14e) | |
|  | | (14f) |

Constraint (14b) guarantees that for each *ONU-BSn*, the sum of the power consumed by wireless signal transmission, caching and the circuit should not exceed the maximum power limitation. Constraint (14c) means that the requested transmission rate of the files which are not be cached by all ONU-BSs to the core network should not exceed the channel capacity constraint of PON. Constraint (14d) makes sure that for each *ONU-BSn*, the total number of bits of the cached files should not exceed its maximum caching capacity. Constraint (14e) guarantees that for each *UEj*, its assigned wireless transmission rate by ONU-BS should not be lower than its minimum receiving rate limit, in order to guarantee its QoS.

## Caching Selection Strategy

We map the selection of cache files to a 0/1 knapsack problem. For ﬁle (k ∈F), its size is denoted by (bits). The popularity it is required by UE is denoted as . The cache decision on the at *ONU-BSn* is denoted as . More specifically, means that *ONU-BSn* is going to cache the file and vice versa. Accordingly, there are only two states for a single file, either fully cached or not cached. That is, you cannot split a file for caching. This is based on the continuity characteristic constraints of optical network transmission. The greedy algorithm often used to solve the knapsack problem cannot guarantee that the item with the highest unit weight value will be taken under this condition. Therefore, we introduce dynamic programming to solve this problem. For dynamic programming, the core thing is to find the state transfer function. When deciding whether to put the i-th file in the cache, we follow the following principles: if the i-th file is placed in the cache, the overall throughput is increased, it is determined to be placed; otherwise, it is not placed. It should be noticed that although we are loading inside, we may take it outside. Due to capacity constraints, it may need to get one out of it in order to put in the i-th one.

We use to represent the largest value obtained by putting the first k items into the caching unit of *ONU-BSn* with the caching power limitation of . We use a top-down perspective. If we have reached the last step (i.e., the maximum throughput obtained by putting k files in the caching unit of *ONU-BSn*), then we have two options:

Without the k-th file, the total throughput is

|  |  |
| --- | --- |
|  | (15a) |

Put the k-th file in, the total throughput is

|  |  |
| --- | --- |
|  | (15b) |

The solution with the largest total value T of the (15a) and (15b) is our final solution. The state transfer function is as follows

|  |  |
| --- | --- |
|  | (16) |

And thereby we can write the system state transition equation as

|  |  |
| --- | --- |
|  | (17) |

Using a dynamic programming algorithm, we can iteratively calculate a cache file selection strategy={} that maximizes system throughput under a given cache power limit.

## Reformulation and Solution of Problem P1

Problem P1 is a typical Mixed Integer Programming (MIP) problem, which is non-linear and non-convex. In this section, we prove that by considering the limitations of optical domains, the problem can be reformulated into a convex optimization problem, with ﬁxed {} calculated by CFSS. Therefore, by deriving the Karush-Kuhn-Tucker (KKT) conditions, we can get the optimal solution to transmission power allocation. Three propositions are proofed and commonly contribute to the reformulation.

**Proposition 1.** For Problem P1, under no circumstances should the equal sign be taken in the inequality constraints (14c) and (14d) at the same time.

**Proof.** For (14c), if the requested transmission rate of the files which are not be cached by all ONU-BSs to the core network exactly equals the channel capacity constraint of PON, the system is falling into an unsustainable situation, which means it can no longer accommodate any new service requests due to the exhaustion of spectrum resource. What’s more, the reservation for protection bandwidth in PON is essential. Although the protection bandwidth does not participate in the transmission of data files, it helps to resist the inevitable non-linear impairments and interferences between carriers in the optical fiber transmission process.

For (14d), due to the flexible range of the file size, the condition for the equal sign is in most cases means splitting the file for caching. Based on the continuity characteristic constraints of optical network transmission, the operation is not preferred. Meanwhile, fully utilizing the storing capacity of ONU-BS would reduce its lifetime and therefore increasing the cost for maintenance of the system.

**Proposition 2.** Maximum throughput can be obtained only when each ONU consumes the maximum power.

**Proof.** Suppose that there exists which satisﬁes

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| --- | --- |
|  | (18) |

that makes the objective function achieve the maximum value

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| --- | --- |
|  | (19) |

Obviously, is an increasing function for . Therefore, can increase its total consumed power by and continue to divide these reserved power into two parts, one for requesting more cache files, and one for increasing wireless transmit power. This, of course, improves the transmission rate obtained by the UE, which also improves network throughput. In this case, we can evolve the objective function value to

|  |  |
| --- | --- |
|  | (20) |

Since , we get the conclusion that the downlink throughput of the WOBAN is maximized only when each *ONU-BSn* consume the maximum level of power.

By using Proposition 1, 2,

Based on the general relationship between the original problem and the dual problem, we have

|  |  |
| --- | --- |
|  | (19) |

**Proposition 3.** For Problem P1, it can be formed as a generalized Lagrangian Problem where the original optimization problem and the dual optimization problem are equivalent.

**Proof.** Let

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| --- | --- |
|  | (20) |

then we have

|  |  |
| --- | --- |
|  | (21) |

which represents that when the allocated wireless transmit power is considered as an independent variable, the objective function of Problem P1 is decreasing and strictly concave.

Let

In the case of Problem P1, we have

The Lagrangian of P1 can be given as

|  |  |
| --- | --- |
|  | (18) |

where λ,µ ∈ , ∈are Lagrangian multipliers.

The KKT Conditions of Problem P1 is expressed as

where (8a) is a necessary condition for an optimal solution, (8b), (8c) and (8d) represent the complementary slackness, and (8e) represents the dual feasibility.

After proving the above three propositions, Problem P1 can be mapped into a MCKP. By using CFSS mentioned previously, the solution space of problem P1 is greatly reduced. We denote the solution space of problem P1 by A, thus we have that

|  |  |
| --- | --- |
|  | (22) |

We denote the element of A as , which represents a pair of caching file selection and wireless power allocation schemes that acts on network throughput. Let denotes whether is chosen to be the solution, where we have . More specifically, means that is chosen to be the solution and vice versa.

Let to be the backhaul bandwidth occupied by *ONU-BSn* with respect to solution , where we have

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| --- | --- |
|  | () |

Likewise, deﬁne to be the sum rate of UE associated to *ONU-BSn* with respect to solution , where we have

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| --- | --- |
|  | () |

Then problem P1 can be converted into the problem of determining the value of with the aim to maximize the downlink wireless access throughput of the B5G WOBAN as follows,

P2:

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| --- | --- |
|  | () |

s.t.

|  |  |
| --- | --- |
|  | () |
|  | () |
|  | () |

Problem P2 is in the form of a multiple-choice knapsack problem (MCKP) [13, Chapter 11]. The problem is to choose no more than one item from each class such that the proﬁt sum is maximized without exceeding the capacity C in the corresponding backhaul limitation. Considering an optimal solution to the MCKP problem, it is obvious that by removing any class n from the optimal MCKP packing, the remaining solution set must be an optimal solution to the subproblem deﬁned by capacity C −ω(Anj) and class set N\{n}. Any other choice will risk to diminish the optimal solution value. Hence, problem P2 has the property of an optimal substructure as described in [14, Section 15.3].

## Proposed Algorithm

We design an optimal and efﬁcient algorithm through dynamic programming based on VABWF method as outlined in Algorithm 1. Deﬁne R(n,c) to be the maximum downlink throughput of the FiWi access network on the condition that there exist only the ﬁrst n classes with backhaul limitation c. Then we can consider an additional class to calculate the corresponding maximum throughput and the following recursive formula describe how the iteratively method is performed

|  |  |
| --- | --- |
|  | () |

Note that the constraint (17c) is satisﬁed by placing the recursive formula in the innermost loop. At each iteration, we choose the optimum solution to the given number of classes n and bandwidth limitation c. The running time of Algorithm 1isdominatedbythe c iterations of the second for-loop, each of which contains at most J iterations where a new solution of a subproblem is computed. Considering N ONU-APs in the B5G WOBAN, there are N subproblems to be computed, so the overall time complexity is O(NCJ).

|  |  |
| --- | --- |
| Algorithm1:Dynamic Programming Algorithm for P2 | |
| Input: N, J, K, W, , C, , , , , , ; | |
| Output: , ; | |
| 1: |  |
|  |  |

robler, we consider the common caching device, high-speed solid state disk (SSD), for caching ﬁles at ONU-BS. The value of ω for SSD is 6.25×10−12 watt/bit. For each ONU-BS, it can adjust the transmission power and the caching power to achieve higher throughput without violating the maximum power constraint PM, namely,

For notational convenience, the circuit power is omitted for it is a constant [14].

equations consecutively with equation numbers in parentheses flush with the right margin, as in (1). First use the equation editor to create the equation. Then select the “Equation” markup style. Press the tab key and write the equation number in parentheses. To make your equations more compact, you may use the solidus ( / ), the exp function, or appropriate exponents. Use parentheses to avoid ambiguities in denominators. Punctuate equations when they are part of a sentence, as in

(1)

Be sure that the symbols in your equation have been defined before the equation appears or immediately following. Italicize symbols (*T* might refer to temperature, but T is the unit tesla). Refer to “(1),” not “Eq. (1)” or “equation (1),” except at the beginning of a sentence: “Equation (1) is ... .”

|  |  |
| --- | --- |
|  | () |

# Simulation and Discussion

Use either SI (MKS) or CGS as primary units. (SI units are strongly encouraged.) English units may be used as secondary units (in parentheses). This applies to papers in data storage**.** For example, write “15 Gb/cm2 (100 Gb/in2).” An exception is when English units are used as identifiers in trade, such as “3½-in disk drive.” Avoid combining SI and CGS units, such as current in amperes and magnetic field in oersteds. This often leads to confusion because equations do not balance dimensionally. If you must use mixed units, clearly state the units for each quantity in an equation.

The SI unit for magnetic field strength *H* is A/m. However, if you wish to use units of T, either refer to magnetic flux density *B* or magnetic field strength symbolized as µ0*H*. Use the center dot to separate compound units, e.g., “A·m2.”

# Conclusion

In this paper, we equip ONU-APs with caches in FiWi access networks to deal with ﬁber backhaul bottleneck and further enhance the system throughput. To achieve the optimal downlink wireless access throughput, we propose a dynamic programming algorithm based on VABWF to perform joint power allocation and caching optimization. Simulation results show that the proposed algorithm outperforms full-cache and random algorithms as well as equal power allocation algorithm signiﬁcantly in terms of system throughput.

Acknowledgment

The preferred spelling of the word “acknowledgment” in American English is without an “e” after the “g.” Use the singular heading even if you have many acknowledgments. Avoid expressions such as “One of us (S.B.A.) would like to thank ... .” Instead, write “F. A. Author thanks ... .” In most cases, sponsor and financial support acknowledgments are placed in the unnumbered footnote on the first page, not here.

References

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1. G. O. Young, “Synthetic structure of industrial plastics,” in Plastics, vol. 3, Polymers of Hexadromicon, J. Peters, Ed., 2nd ed. New York, NY, USA: McGraw-Hill, 1964, pp. 15-64. [Online]. Available: http://www.bookref.com.
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3. The Terahertz Wave eBook. ZOmega Terahertz Corp., 2014. [Online]. Available: http://dl.z-thz.com/eBook/zomega\_ebook\_pdf\_1206\_sr.pdf. Accessed on: May 19, 2014.
4. Philip B. Kurland and Ralph Lerner, eds., *The Founders’ Constitution.* Chicago, IL, USA: Univ. of Chicago Press, 1987, Accessed on: Feb. 28, 2010, [Online] Available: http://press-pubs.uchicago.edu/founders/

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J. K. Author, “Name of paper,” *Abbrev. Title of Periodical*, vol. *x*, no. *x*, pp. *xxx-xxx*, Abbrev. Month, year. Accessed on: Month, Day, year, DOI: 10.1109.*XXX*.123456, [Online].

*Examples:*

1. J. S. Turner, “New directions in communications,” *IEEE J. Sel. Areas Commun*., vol. 13, no. 1, pp. 11-23, Jan. 1995.
2. W. P. Risk, G. S. Kino, and H. J. Shaw, “Fiber-optic frequency shifter using a surface acoustic wave incident at an oblique angle,” *Opt. Lett.*, vol. 11, no. 2, pp. 115–117, Feb. 1986.
3. P. Kopyt *et al., “*Electric properties of graphene-based conductive layers from DC up to terahertz range,” *IEEE THz Sci. Technol.,* to be published. DOI: 10.1109/TTHZ.2016.2544142.

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J.K. Author. (year, month). Title. presented at abbrev. conference title. [Type of Medium]. Available: site/path/file

*Example:*

1. PROCESS Corporation, Boston, MA, USA. Intranets: Internet technologies deployed behind the firewall for corporate productivity. Presented at INET96 Annual Meeting. [Online]. Available: http://home.process.com/Intranets/wp2.htp

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1. R. J. Hijmans and J. van Etten, “Raster: Geographic analysis and modeling with raster data,” R Package Version 2.0-12, Jan. 12, 2012. [Online]. Available: http://CRAN.R-project.org/package=raster
2. Teralyzer. Lytera UG, Kirchhain, Germany [Online]. Available: http://www.lytera.de/Terahertz\_THz\_Spectroscopy.php?id=home, Accessed on: Jun. 5, 2014

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Legislative body. Number of Congress, Session. (year, month day). *Number of bill or resolution*, *Title*. [Type of medium]. Available: site/path/file

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*Example:*

1. U.S. House. 102nd Congress, 1st Session. (1991, Jan. 11). *H. Con. Res. 1, Sense of the Congress on Approval of Military Action*. [Online]. Available: LEXIS Library: GENFED File: BILLS

*Basic format for patents (when available online):*

Name of the invention, by inventor’s name. (year, month day). Patent Number[Type of medium]. Available: site/path/file

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1. Musical toothbrush with mirror, by L.M.R. Brooks. (1992, May 19). Patent D 326 189

[Online]. Available: NEXIS Library: LEXPAT File: DES

*Basic format for conference proceedings (published):*

J. K. Author, “Title of paper,” in *Abbreviated Name of Conf.*, City of Conf., Abbrev. State (if given), Country, year, pp. *xxxxxx.*

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1. D. B. Payne and J. R. Stern, “Wavelength-switched pas- sively coupled single-mode optical network,” in *Proc. IOOC-ECOC,* Boston, MA, USA,1985,   
   pp. 585–590.

*Example for papers presented at conferences (unpublished):*

1. D. Ebehard and E. Voges, “Digital single sideband detection for interferometric sensors,” presented at the *2nd Int. Conf. Optical Fiber Sensors,* Stuttgart, Germany, Jan. 2-5, 1984.

*Basic format for patents:*

J. K. Author, “Title of patent,” U.S. Patent *x xxx xxx*, Abbrev. Month, day, year.

*Example:*

1. G. Brandli and M. Dick, “Alternating current fed power supply,” U.S. Patent 4 084 217, Nov. 4, 1978.

*Basic format**for theses (M.S.) and dissertations (Ph.D.):*

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b) J. K. Author, “Title of dissertation,” Ph.D. dissertation, Abbrev. Dept., Abbrev. Univ., City of Univ., Abbrev. State, year.

*Examples:*

1. J. O. Williams, “Narrow-band analyzer,” Ph.D. dissertation, Dept. Elect. Eng., Harvard Univ., Cambridge, MA, USA, 1993.
2. N. Kawasaki, “Parametric study of thermal and chemical nonequilibrium nozzle flow,” M.S. thesis, Dept. Electron. Eng., Osaka Univ., Osaka, Japan, 1993.

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b) J. K. Author, “Title of paper,” unpublished.

c) J. K. Author, “Title of paper,” to be published.

*Examples:*

1. A. Harrison, private communication, May 1995.
2. B. Smith, “An approach to graphs of linear forms,” unpublished.
3. A. Brahms, “Representation error for real numbers in binary computer arithmetic,” IEEE Computer Group Repository, Paper R-67-85.

*Basic formats for standards:*

a) *Title of Standard*, Standard number, date.

b) *Title of Standard*, Standard number, Corporate author, location, date.

*Examples:*

1. IEEE Criteria for Class IE Electric Systems, IEEE Standard 308, 1969.
2. Letter Symbols for Quantities, ANSI Standard Y10.5-1968.

*Article number in reference examples:*

1. R. Fardel, M. Nagel, F. Nuesch, T. Lippert, and A. Wokaun, “Fabrication of organic light emitting diode pixels by laser-assisted forward transfer,” *Appl. Phys. Lett.*, vol. 91, no. 6, Aug. 2007, Art. no. 061103.
2. J. Zhang and N. Tansu, “Optical gain and laser characteristics of InGaN quantum wells on ternary InGaN substrates,” *IEEE Photon. J.*, vol. 5, no. 2, Apr. 2013, Art. no. 2600111

*Example when using et al.:*

1. S. Azodolmolky *et al.*, Experimental demonstration of an impairment aware network planning and operation tool for transparent/translucent optical networks,” *J. Lightw. Technol.*, vol. 29, no. 4, pp. 439–448, Sep. 2011.

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   T. C. Author is with the Electrical Engineering Department, University of Colorado, Boulder, CO 80309 USA, on leave from the National Research Institute for Metals, Tsukuba, Japan (e-mail: author@nrim.go.jp). [↑](#footnote-ref-1)