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MONOGRAPH ON MATHEMATICAL MODELLING OF C-RAN

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ABSTRACT

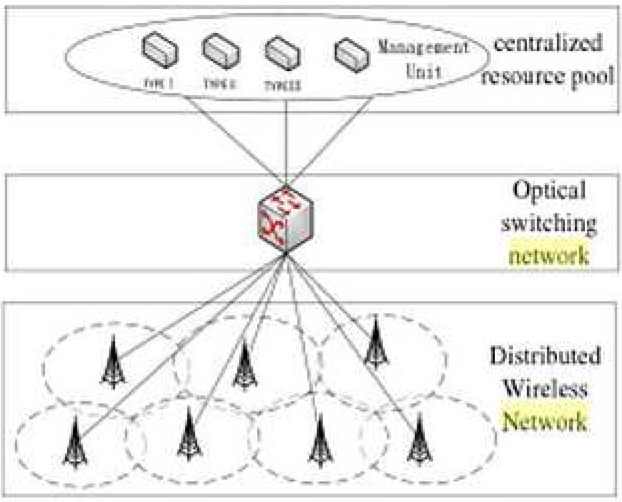
In this paper, a multidimensional Markov model has been proposed for Cloud Radio access network (C-RAN) to overcome the efficiency and flexibility issues with the traditional RAN architecture. Traditional model lacks the sophisticated mathematical model to analyse the stochastic multiplexing gain from the pooling of Virtual base stations (VBSs). To determine the pooling gain, a product-form solution for the stationary distribution has been derived and and a recursive method has been presented to calculate the blocking probabilities.

KEYWORDS
cloud radio access, cloud computing, markov model.

INTRODUCTION
Centralized Radio Access Network is a real time cloud infrastructure and open platform access network. The architecture requires a centralized resource pool which dynamically handles the cell load. The key is to how to have fewer resources handle a cell load keeping the performance optimized.
As the number of mobile subscriber growth and huge demand of data services, the traditional RAN is difficult to meet up the demand, and therefore, the architecture of RAN is to be altered to adapt to the new environment. Some scholars have proposed an architecture based on centralized RAN, an open-platform for real-time cloud radio access network for better resource utilization, extended life of the equipments and more importantly, better service provided to the customers.

ARCHITECTURE OF C-RAN
C-RAN is a new evolution of wireless access network. It uses optical switching transmission network to link the Remote Radio Units (RRUs) and the nodes of centralized resource pool such as Baseband Units (BBUs) in order to achieve large-scale regional coverage of the base stations. One BBU can handle some loads of RRUs. The distributed RRUs constitute cell cluster according to geographical proximity.

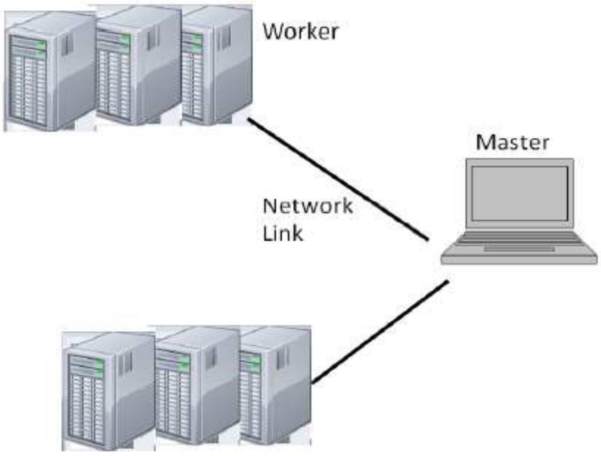
FIGURE 1: ARCHITECTURE OF C-RAN



BASICS OF CLOUD TECHNOLOGY
Cloud Computing is a relatively new technology to provide users with services, which are accessible through networks including local area network (LAN), wide area network (WAN) or even Internet. More precisely, a Cloud computing platform is based on two types of software: end users' applications and system software. The end users' applications are delivered as services to users, known by softwares as a service (SaaS) and the system software is a middleware in support of those services with a quality of service according to a Service Level Agreement. Complicated applications often require a huge amount of available computing processing and network capacity, provided as an infrastructure as a service (IaaS), in support of large-scale experiments. In this work, focus is on divisible load applications, where we impinge the concept of modularity. The application load is grouped into a number of tasks that can be processed in parallel but independently. Divisible Load Theory is centered on the master-slave model. The master is a processor which divides an application load into tasks and assigns each task to a separate slave/worker.

SYSTEM MODELING (STAR-TOPOLOGY)
Cloud generally comprises of multiple Computing Workers and a single Master Worker, where these computing workers are independently connected to the master worker in a star topology. It's to be noted that the data speed of the link connecting these computing workers and the master worker dictates the speed of communication processing when a data is transmitted. Upon receiving of an application or service request from an user in the network, the master divides the whole application into small segments of tasks in a sequential pattern. Certain amount of overhead is associated with each task for transmission and for purpose of computing. To minimize the overheads, the master worker includes a scheduler which must take into account of the capacity of the selected computing workers in terms of the capacity of the communication link between the master and the computing slave/worker. In this paper, the pivotal point is on the statistics of computing process at the workers under various conditions, and to determine utilization of a computing worker and the corresponding total blocking probability.
The following figure demonstrates A Star-Topology Computing Platform Model.

FIGURE 2



A Cloud is considered to have R heterogeneous computing workers. A computing worker r, r ∈ {1,.., R}, in the Cloud is modeled by a tandem processing system which comprises of of three components. The first component implies the task receiving processing capacity of $\mu_{1,r}$ tasks per second, r being index of computing worker. The second component denotes the capacity of $\mu_{2,r}$ tasks per second, and the third one indicates the task transmission capacity of $\mu_{3,r}$. It is assumed that all the computing workers can run in parallel, but our model does not impose this and computing workers may run at different stages during application execution.

An application can be either dynamically submitted to the Cloud to run or sometimes it may happen that the application is in static in cloud server but the server can receive dynamic requests from the end users.. Applications' or execution requests' arrival is assumed to be a Poisson process with a mean rate λ. When an application arrives at the Cloud, the master worker segments the application into R tasks to be assigned for each individual computing worker. The task assigned to a computing worker r is $\alpha_r\lambda$, which is also a Poisson process. Note that α_r is the weight of a task load assigned to a computing worker r and the whole application load is given as below:

$$\alpha_r = \sum_{r=1}^{r=R} \alpha_r = 1$$

MODELING OF A DIVISIBLE LOAD THEORY IN A STAR NETWORK CLOUD USING MARKOV PROCESS

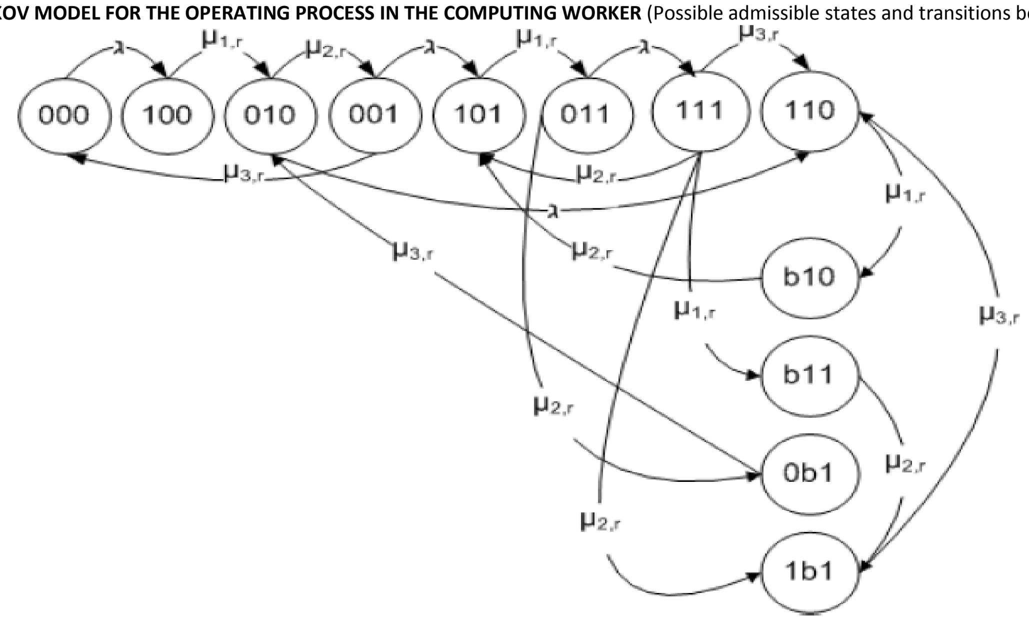
Each computing worker consists of three process components, including task receiving process denoted as S1 (stands for station 1), a process denoted as S2 (stands for Station 2) and a transmission process delineated as S3 (stands for Station 3). The S1 makes a note of the time delay needed for receiving a task from the master worker before starting the computing process. The S2 checks the time needed to execute the received task. The Station 3 defines the time needed to transfer the result obtained at the Station 2 back to the master worker.

These three stations, associated with a computing worker r ∈{1,2,…,R}, are connected in a tandem model without any queuing spaces. Probability distribution of receiving tasks at the S1 is a Poisson process and the entire process of receiving tasks from master to the worker is µ-distribution with a mean value of $\mu_{1,r}$ tasks per second since each task is accumulated by a bulk of data packets in sequence order with Poisson distribution. Likewise, the processing at the S2 is another µ-distribution with a mean value of of $\mu_{2,r}$ tasks per second. The transmission of the results back to master worker at the Station 3 is performed in a manner that the results are packetized into data packets with exponential distribution, so that the transmission time of each packet is also exponentially distributed. Hence, the transmission of tasks at the Station 3 is exponentially distributed with a mean value of $\mu_{3,r}$ tasks per second. A computing worker r is a process chain which is connected sequentially. The master does not assign any new task to the slave/worker is the application is in process in S1 even if S2 and S3 are free.

A 3-digit symbol is used to represent the operation status of a computing worker, where digit "0" represents the processor in an "idle" status and "1" represents the processor in a "busy" status. For example, symbol "101" represents that the process of receiving a task from the master worker is on-going, the computing processor is "free" and that the transmitting processor is "busy" on sending the results back to master worker. Furthermore, the status "b" represents an application task that is blocked due to one application task's arrival into a processor in "busy" status. For example, symbol "b11" represents that when a completely received application task is sent to a computing processor, this application task is blocked due to the computing processor being in a "busy" status, meanwhile, the transmitting processor is also in a "busy" on sending results back to master worker. The description of the individual states has been depicted below:

000	System is empty.
100	Application task is in process at Station 1 only.
110	Application tasks are in process at Station 1 and 2 only.
111	Application tasks are in process at Station 1, 2 and 3.
101	Application tasks are in process at Station 1 and 3 only.
001	Application task is in process at Station 3 only.
011	Application tasks are in process at Station 2 and 3 only.
010	Application task is in process at Station 2 only.
b10	Application task is blocked at the output of Station 1 because Station 2 is occupied.
b11	Application task is blocked at the output of Station 1 because both Station 2 and 3 are occupied.
0b1	Application task is blocked at the output of Station 2 because Station 3 is occupied.
1b1	Application task is blocked at the output of Station 2 because both Station 1 and 3 are occupied.

FIGURE 3: MARKOV MODEL FOR THE OPERATING PROCESS IN THE COMPUTING WORKER (Possible admissible states and transitions between them)



Considering the state "000", which is directly related to the two states "100" and "001". When the computing worker in state "000" is starting to receive a new task from the master, it moves to state "100" at the rate of λ which is an outbound flow from the state "000". On the other hand, when the computing worker is in state "001" completes the process of transmitting data back to the master.

worker, it transits to state "000" at the rate of $\mu_{3,r}$, which is an inbound flow into the state "000". When the operation is stable, the outbound flows from the state "000" is equal to the inbound flows to the state "000". Consequently, we obtain Equation (1) as:

$$\alpha_r \lambda p_{000} = \mu_{3r} p_{001} \quad \text{------------(1)}$$

The left side and the right side denote outbound flow the inbound flow respectively.

Similarly, applying the same strategy to the rest of the states, we can obtain the following equations (2)–(12) for all the corresponding states. The steady-state equations for this multidimensional Markov chain are then as follows:

$$\mu_{1,r} p_{100} = \alpha_r \lambda p_{000} + \mu_{3r} p_{101} \quad \text{-------------(2)}$$

$$(\alpha_r \lambda + \mu_{2,r}) p_{010} = \mu_{1,r} p_{100} + \mu_{3,r}(p_{011} + p_{0b1}) \quad \text{--------------(3)}$$

$$(\alpha_r \lambda + \mu_{3,r}) p_{001} = \mu_{2,r} p_{010} \quad \text{----------------(4)}$$

$$(\mu_{1,r} + \mu_{3,r}) p_{101} = \alpha_r \lambda p_{001} + \mu_{2,r}(p_{110} + p_{b10}) \quad \text{-------------(5)}$$

$$(\alpha_r \lambda + \mu_{2,r} + \mu_{3,r}) p_{011} = \mu_{1,r} p_{101} \quad \text{---------------(6)}$$

$$(\mu_{1,r} + \mu_{2,r} + \mu_{3,r}) p_{111} = \alpha_r \lambda (p_{011} + p_{0b1}) \quad \text{------------------(7)}$$

$$(\mu_{1,r} + \mu_{2,r}) p_{110} = \alpha_r \lambda p_{010} + \mu_{3,r}(p_{111} + p_{b11} + p_{1b1}) \quad \text{-------(8)}$$

$$(\alpha_r \lambda + \mu_{3,r}) p_{0b1} = \mu_{2,r} p_{011} \quad \text{------------------(9)}$$

$$(\mu_{1,r} + \mu_{3,r}) p_{1b1} = \mu_{2,r}(p_{111} + p_{b11}) \quad \text{----------------(10)}$$

$$(\mu_{1,r} + \mu_{3,r}) p_{1b1} = \mu_{2,r}(p_{111} + p_{b11}) \quad \text{--------------(11)}$$

$$\mu_{2,r} p_{b10} = \mu_{1,r} p_{111} \quad \text{-------------(12)}$$

We can solve the mentioned steady-state probabilities in terms of a single variable i.e. p000 and using boundary equation $\Sigma\Sigma\Sigma p n1, n2, n3 = 1$ to find p000 as follows:

Based on Equation (1), we obtain:

$$p_{001} = \frac{\alpha_r \lambda}{\mu_{3,r}} p_{000} \quad \text{------------(13)}$$

From Equations (4) and (13), we obtain the following formula:

$$p_{010} = \frac{\alpha_r \lambda (\alpha_r \lambda + \mu_{3,r})}{\mu_{3,r} \mu_{2,r}} p_{000} \quad \text{----------------(14)}$$

From Equations (2), (3), (6), and (9) we obtain by substitutions the following equation:

$$p_{101} = \frac{\alpha_r \lambda \mu_{3,r}(\alpha_r \lambda + \mu_{2,r})p_{010} - \alpha_r^2 \lambda^2 \mu_{3,r} p_{000}}{\alpha_r \lambda \mu_{3,r}^2 + \mu_{1,r}\mu_{3,r}}$$ ----------(15)

Consequently, p011 is obtained from Equation (6) as follows:

$$p_{011} = \frac{\mu_{1,r}}{\alpha_r \lambda + \mu 2, r \mu 3, r} p_{101}$$ ---------------(16)

p0b1 is obtained based on Equations (9), and (16):

$$p_{0b1} = \frac{\mu_{2,r}}{\alpha_r \lambda + \mu_{3,r}} p_{011}$$ ----------------(17)

Based on Equation (7), p111 is obtained as follows, and then can be computed from Equations (16) and (17):

$$p_{111} = \frac{\alpha_r \lambda}{\mu_{1,r} + \mu_{2,r} + \mu_{3,r}} (p_{011} + p_{0b1})$$ --------------------(18)

From Equation (12), we obtain:

$$p_{b10} = \frac{\mu_{1,r}}{\mu_{2,r}} p_{111}$$ --------------(19)

Based on Equation (5), we obtain:

$$p_{110} = \frac{1}{\mu_{2,r}} [(\mu_{1,r} + \mu_{3,r})p_{101} - \alpha_r \lambda p_{001} - \mu_{2,r} p_{b10}]$$ ---(20)

Based on Equations (10) and (11), pb11 is obtained using the following formula:

$$p_{b11} = \frac{\mu_{1,r}^2 + \mu_{1,r}\mu_{3,r} + \mu_{1,r}\mu_{2,r}}{\mu_{1,r}\mu_{3,r} + \mu_{2,r}\mu_{3,r} + \mu_{3,r}^2} p_{111}$$ ---------(21)

From Equation (10), we obtain:

$$p_{1b1} = \frac{\mu_{2,r}}{\mu_{1,r} + \mu_{3,r}} (p_{111} + p_{b11})$$ ---------------(22)

The total task blocking probability in computing worker r is given by the following formula, which denotes as well the computing worker efficiency:

$$P_b = p_{b11} + p_{1b1} + p_{b10} + p_{0b1}$$ ----------(23)

EXTENSION OF MULTIDIMENSIONAL MARKOV PROCESS INTO C-RAN

The proposed model is being introduced and with proof for its reversibility. The essence of the model is a Virtual Base Station cluster with M number of Virtual Base Stations. Let us assume that these VBSs share N number of servers. Each VBS is connected to a remote radio unit (RRU) and endowed with K numbers of radio resources.

User sessions arrive independently in the coverage area of these VBSs following identical independent Poisson processes with arrival rate λ, and are served independently with exponential service time with mean μ^{-1}. We assume exponential service time basing on the assumption that the length of users' data queue is distributed as per Poisson's distribution. Defining the number of sessions in the m-th VBS to be k_m, then the number of sessions in all the pooled VBSs can be described with an M-dimensional vector as follows: $k = (k_1, \cdots, k_m, \cdots, k_M)^T$.

Each active user session simultaneously occupies a radio server and a cloud server, and releases both type of servers after being served. When a user session arrives, the pool scheduler monitors the number of radio servers and cloud servers to decide whether the session would be accepted or not. The condition of the session to be accepted is when the number of radio servers in the serving VBS is less than K and the number of cloud servers in the pool is less than N. Otherwise the session is rejected by the scheduler. This blocking policy reflects the constraint by both radio and computational resources.

Taking the blocking policy into consideration, the set of possible states can be defined as follows:

$$\mathbb{K} = \{k \mid 0 \le k_1, \cdots, k_M \le K, \quad 0 \le \sum_{m=1}^{M} k_m \le N\}$$ ----------------(1)

TRANSITION RATES

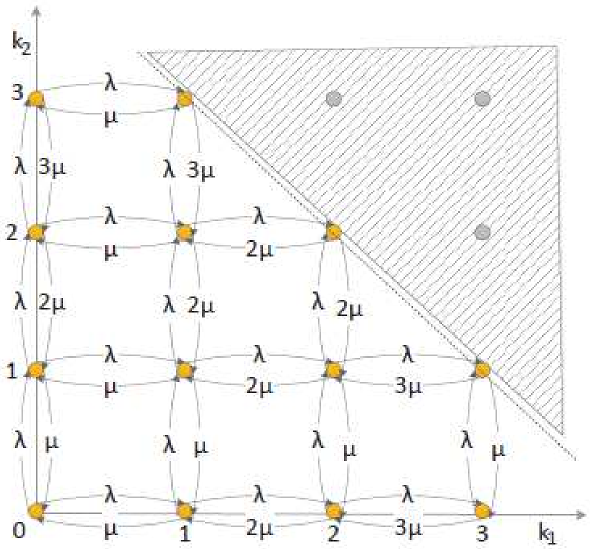
The state of k changes as user sessions arrive and depart. We can assume that there can only be a single session arrival or departure at any point of time. Thus, only a single value of k can change at any epoch, and the change is either +1 or −1. In other words, k is a M-dimensional Markovian chain process and the rate of transition from state $k^{(i)}$ to state $k^{(j)}$ as:

$$q_{k^{(i)}k^{(j)}} = \begin{cases} \lambda, & \text{if } k^{(j)} - k^{(i)} = e_m \\ k^i_m \mu, & \text{if } k^{(j)} - k^{(i)} = -e_m \\ 0, & \text{otherwise} \end{cases}$$ ---------------(2)

where states $k^{(i)}, k^{(j)} \in \mathbb{K}$, $k^{(i)}_m$ is the m-th entry of $k^{(i)}$, and $e^T_m = (0, \cdots, 0, \underbrace{1}_{m\text{-th}}, 0, \cdots, 0)$.

For the ease of understanding, following figure illustrates the state transition graph of a simple example with N = 4, M = 2 and K = 3.

FIGURE 4



Transition graph of a pool with 2 VBSs. K = 3, N = 4.

PROPOSED STATIONARY DISTRBUTION

Since k is reversible, the local balance equation:

$$P(k^{(i)}) \cdot q_{k^{(i)}k^{(j)}} = P(k^{(j)}) \cdot q_{k^{(j)}k^{(i)}}$$ ----------(3)

holds for the statistical equilibrium of k. Without loss of generality, let

$$k^{(i)} = (k_1, \cdots, k_m, \cdots, k_M)^T$$

$$k^{(j)} = (k_1, \cdots, k_m + 1, \cdots, k_M)^T,$$

and substitute (2) into (3), we can get

$$P(k_1, \cdots, k_m, \cdots, k_M) \cdot \lambda$$
$$= P(k_1, \cdots, k_m + 1, \cdots, k_M) \cdot (k_m + 1)\,\mu$$ -------------(4)

After a simple manipulation on (4), we have

$$\frac{P(k_1, \cdots, k_m + 1, \cdots, k_M)}{P(k_1, \cdots, k_m, \cdots, k_M)} = \frac{a}{(k_m + 1)}$$ --------------(5)

where a = λ/μ. Clearly, this is a recursive equation for computing the stationary distribution. Continuing the recursion down to 0 for the m-th iterative value of k,

$$P(k_1, \cdots, k_m, \cdots, k_M)$$
$$= P(k_1, \cdots, 0, \cdots, k_M) \cdot \frac{a^{k_m}}{k_m!}$$ ----------------(6)

Then repeat the same process for other values of k/ other entries of k, we can define the distribution of k:

$$P(k) = P_0 \cdot \prod_{m=1}^{M} \frac{a^{k_m}}{k_m!}$$ ---------(7)

In which

$$P_0 = P(0,\cdots,0,\cdots,0) = \left(\sum_{k\in\mathbb{K}}\prod_{m=1}^{M}\frac{a^{k_m}}{k_m!}\right)^{-1}$$ -------------(8)

Can be derived from the statistical fact that

$$\sum_{k\in\mathbb{K}} P(k_1,\cdots,k_m,\cdots,k_M) = 1$$ -------------(9)

BLOCKING PROBABILITY

Let us decompose the blocking events into two sets. We define the blocking events that are solely due to insufficient radio servers i.e. **radio blocking** and can be mathematically defined as:

$$k_m^- = K, \sum_{i=1}^{M} k_i^- < N)$$

And blocking due to insufficient cloud servers i.e **Cloud blocking** and can be defined as follows:

$$\sum_{i=1}^{M} k_i^- = N)$$

the union set of radio and cloud locking events to be overall blocking. These two blocking probabilities are mutually exclusive.
With above definition, we have overall blocking probability
Pb = Pbr + Pbc------------(9)
with the probability of radio blocking

$$P_{br}(N,M) = \begin{cases} \sum_{m=1}^{M}\frac{1}{M}\sum_{k\in\mathbb{K}^{m,K}_{<N}} P(k), & N > K \\ 0, & N \le K \end{cases}$$
$$= \begin{cases} \frac{P_0}{M}\sum_{m=1}^{M}\sum_{k\in\mathbb{K}^{m,K}_{<N}}\prod_{m=1}^{M}\frac{a^{k_m}}{k_m!}, & N > K \\ 0, & N \le K \end{cases}$$ ----------------(!0)

And the probability of the cloud blocking:

$$P_{bc}(N,M) = \sum_{k\in\mathbb{K}_{=N}} P(k)$$
$$= P_0\cdot\sum_{k\in\mathbb{K}_{=N}}\prod_{m=1}^{M}\frac{a^{k_m}}{k_m!}$$ ------------------(11)

Where

$$\mathbb{K}_{=N} = \{k|k_1+\cdots,k_M = N\}$$
$$\mathbb{K}^{m,K}_{<N} = \{\mathbb{K}^{m,K}\cap\mathbb{K}_{<N}\}$$
$$\mathbb{K}_{<N} = \{k\|k_1+\cdots,k_M < N\}$$
$$\mathbb{K}^{m,K} = \{k|k_m = K\}.$$

Since equation (7) is symmetric in any two of it's arguments,

$$P(\cdots,k_i,\cdots,k_j,\cdots) = P(\cdots,k_j,\cdots,k_i,\cdots),$$ ------------(12)

then (10) can be simplified for N > K as:

$$P_{br}(N,M) = \frac{M}{M}\sum_{k\in\mathbb{K}^{1,K}_{<N}} P(k)$$
$$= P_0\cdot\sum_{k\in\mathbb{K}^{1,K}_{<N}}\prod_{m=1}^{M}\frac{a^{k_m}}{k_m!}$$
$$= P_0\cdot\frac{a^K}{K!}\cdot\sum_{k\in\mathbb{K}^{1,K}_{<N}}\prod_{m=2}^{M}\frac{a^{k_m}}{k_m!}$$ --------------(13)

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