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Reliability evaluation of linear multi-state consecutively-connected systems constrained by m consecutive and n total gaps

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ABSTRACT

This paper extends the linear multi-state consecutively-connected system (LMCCS) to the case of LMCCS-MN, where MN denotes the dual constraints of m consecutive gaps and n total gaps. All the nodes are distributed along a line and form a sequence. The distances between the adjacent nodes are usually non-uniform. The nodes except the last one can contain statistically independent multi-state connection elements (MCEs). Each MCE can provide a connection between the node at which it is located and the next nodes along the sequence. The LMCCS-MN fails if it meets either of the two constraints. The universal generating function technique is adopted to evaluate the system reliability. The optimal allocations of LMCCS-MN with two different types of failures are solved by genetic algorithm. Finally, two examples are given for the demonstration of the proposed model.

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1. Introduction

In modern satellite communications, the purpose is to send information from one point on earth to another through the satellites in space. The information transmission can be simplified to three procedures. First, a radio in one place on earth emits signals up into space. Then one satellite gathers the signals and retransmits them to other satellites along the communication link. Finally, a remote satellite gets the signals and sends them back down to another spot on earth. The whole satellite communications can be modeled as linear multi-state consecutively-connected systems (LMCCSs). The modern satellite communication plays an increasingly important role in the world economy. Thus, researches on the reliability analysis and optimal allocation for the LMCCS would be meaningful and challenging. Generally, the LMCCS can be used to model many systems, such as the fluid transportation systems, wireless communication systems, sensor systems and logistics systems. The $N+1$ orderly connected nodes are evenly distributed along a line and form a sequence, which forms an LMCCS [1]. The distance between two adjacent nodes is defined as a basic length unit [2]. All the nodes can contain statistically independent multi-state connection elements (MCEs) except the last one. Each MCE j can provide a connection between the node at which it is located and the next nodes X_j along the sequence. The X_j is a positive random variable ($r.v.$) and its probability mass function (PMF) is usually given. Any MCE failure may cause a disconnection of the sequence. In other words, the system fails, if the disconnection of any node exists in the sequence.

The LMCCS model was first proposed in Ref. [1]. Algorithms for its reliability evaluation were studied in Refs. [3,4]. The LMCCS model has a source node and a sink node. It can be generalized to the multistate-node acyclic network model which has a source node and a number of sink nodes [5]. The reliability evaluation of LMCCS with fixed retransmission delays was studied in [6]. The expenses of bypass transportation systems (BTS) in LMCCS are introduced in Ref. [7], where the expenses depend on the number of the gaps and the length of the gaps. The reliability analysis for the BTS (such as oil pipeline transportation system and railway network system) can be referred in Refs. [8–13].

The optimal allocation problem of multi-state elements in LMCCS is introduced by Malinowski and Preuss in Ref. [14]. The optimal allocation elements in LMCCS with the common cause failures are studied in Ref. [15]. Then, a special case of LMCCS is proposed by Levitin [16], in which several multi-state elements

Abbreviations: MCEs, multi-state connection elements; PM-LCCS, phased-mission linear consecutively-connected systems; mGCCS, m consecutive gaps linear multi-state consecutively-connected system; LMCCS, linear multi-state consecutively-connected system; BTS, bypass transportation systems; *r.v.*, random variable; LMCCS-N, linear multi-state consecutively-connected system with the constraint of n total gaps; LMCCS-MN, linear multi-state consecutively-connected system subject to the dual constraints of m consecutive gaps and n total gaps; GA, genetic algorithm; UGF, universal generating function; PMF, probability mass function.

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Nomenclature

E_j	set of consecutively ordered nodes $\{1,...,j\}$
T_j	the most remote location with which the nodes in the set E_j can be connected
G_j	the most remote location with which the node j can be connected directly
$g_{j,k}$	k-th realization of $r.v.$ G_j
$p_{j,k}$	probability of the realization $r.v.$ $g_{j,k}$
$\boldsymbol{G}_j$	vector of different realization of G_j
$\boldsymbol{P}_j$	vector of probabilities of random realization of G_j
$1(A)$	having the value 1 when A is true and the value 0 when A is false

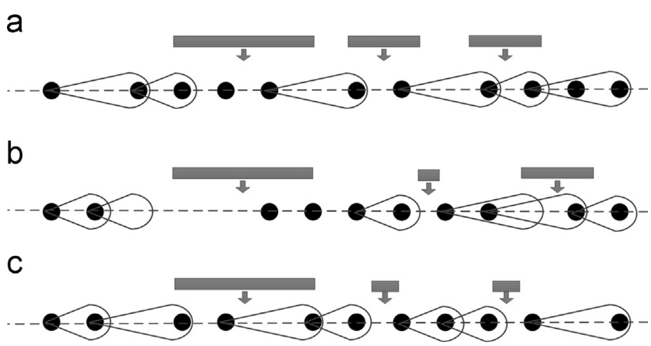

Fig. 1. Linear multistate connected sensors in working state (a), and failed state (b,c).

can be allocated in the same node while some nodes can remain empty. When several elements are allocated in a node, they can be destroyed by common cause failures with the node suffering attack. The optimal maintenance and allocation of elements in LMCCS were solved by Peng et al. in Ref. [17], which is constrained with the system availability requirement. Then, the LMCCS model is extended to the phased-mission linear consecutively-connected systems (PM-LCCS) in Ref. [18]. In each phase, the PM-LCCS can be reduced to an LMCCS model and the nodes are in equidistant locations. The reliability analysis for the phased-mission system is studied in Refs. [19–21]. The PM-LCCS model with common cause failures is studied in Ref. [22].

The LMCCS model was further extended to m consecutive gaps linear multi-state consecutively-connected system (mGCCS) [23]. A gap exists in the sequence if a node cannot be connected with any previous node. The m consecutive gaps in the sequence mean that at least m consecutive nodes cannot be connected with any previous node. The structure of the mGCCS model is the same as that of the traditional LMCCS model. The nodes in the mGCCS model is in equidistant locations along a line, and the system fails as long as there is at least m consecutive gaps. When $m=1$, no gap is allowed, and the mGCCS model reduces to a traditional LMCCS model. The condition of the m consecutive gaps is the only constraint for the mGCCS model. Another generalization of the LMCCS model is the LMCCS with the constraint of n total gaps (LMCCS-N) [2]. The LMCCS-N fails if it contains at least n nodes disconnected with any previous node. In other words, the LMCCS-N fails if the total number of gaps reaches a specified limit n. The structure of the LMCCS-N model is the same as that of the traditional LMCCS model. The nodes in the LMCCS-N model is also in equidistant locations along a line. The traditional LMCCS model is a special case of the LMCCS-N model with $n=1$. Since the LMCCS-N model is only focused on the constraint of the total number of gaps, it is not suitable for the LMCCS with the constraint of consecutive gaps. Another extended model of LMCCS is the LMCCS with the combined gap constraints (m/nCCS) [24]. The m/nCCS model fails if there exist at least m nodes not connected with any previous node or at least n consecutive nodes not connected with any previous node. The structure of the m/nCCS model is the same as that of the traditional LMCCS model. The nodes in the m/nCCS model is also in equidistant locations along a line. In the traditional LMCCS model [1,4,15,16] and its extended models: LMCCS-N [2], mGCCS [23], and m/nCCS [24], the structures are the same and the distances between the adjacent nodes are equal to a basic length unit, which may be not true in many practical applications.

Take the linear wireless sensor networks for example, sensors are usually allocated to the non-uniform distributed nodes along a line. The structure is shown in Fig. 1. Each sensor can cover different zones, which is dependent on the internal operation modes and the external environment factors, and the size of covered zones can vary discretely over different sensors. They must detect some objects that traverse the line. Usually, there are two kinds of objects: small objects and large objects. If a gap exists along the line, some small objects can traverse the line, and cannot be detected. If the number of consecutive gaps exceeds the size of a large object, the large object can traverse the line, and otherwise it cannot pass the line. When the objects pass the line, they cannot be detected, and then the system may not work. The system consists of two different types of failures: one is subject to the number of undetected objects (as shown in Fig. 1(c)), and the other is due to a large object being undetected (as shown in Fig. 1(b)). That is to say, when the number of undetected objects exceeds a pre-specified value by the engineering requirement, the system fails. Moreover, when a large object passes the line, it will be undetected, and then the system fails. When either of the two different types of failures happens, regardless of which one happens first, the system fails. In other words, the system survives if neither of the two different types of failures occurs (as shown in Fig. 1(a)).

The traditional LMCCS model and its extended models: LMCCS-N [2], mGCCS [23], and m/nCCS [24], can also not be applied directly to evaluate the crude oil transportation system with the unevenly distributed nodes. A crude oil transportation system is a linear long distance transport system. It supplies crude oil from oil well to a refinery, which is composed of crude oil transportation pipelines and crude oil pumps. Oil pumps are located at the consecutive nodes between the pipelines. They provide enough pressure to transfer the crude oil. The distances between any two adjacent nodes are usually not equal because of the external environment factors. Fig. 2 shows a crude oil transportation system. Oil pumps are the key instruments in the crude oil transportation system. In certain degree, the crude oil transportation pipelines remain intact. If there exist nodes that are not connected with any previous node, the oil cannot be transferred to these nodes by the system and the dynamic bypass transfer instruments, such as oil truck and tank truck, should be applied. With the constraints, such as transportation capacity, energy consumption and greenhouse gas emissions, the bypass instruments cannot be competent for too many consecutive gaps. Subject to budget cost constraint, the amount of the bypass instruments is also limited, which limits the total number of the gaps. Either when the number of consecutive gaps exceeds one pre-specified value, or when the number of total gaps exceeds some pre-specified value, the system fails.

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