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Optimal arrangement of connecting elements in linear consecutively connected systems with heterogeneous warm standby groups

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ABSTRACT

Motivated by practical applications such as radio communication and flow transmission systems, this paper models and optimizes linear consecutively connected systems (LCCS) with a set of linearly ordered nodes. Each node may contain multiple connection elements (CE) configured as a warm standby structure, where one CE is online providing a connection between its host node and a certain number of next nodes along the sequence, with the remaining CEs serving as standbys. CEs have heterogeneous types characterized by different time-to-failure distributions and connection ranges. An iterative algorithm is first proposed for determining performance stochastic processes of particular CE standby groups. A universal generating function technique is then used for evaluating instantaneous and expected system connectivity for the considered LCCS. An optimization problem of CE distribution and sequencing is further defined and solved, with the objective of finding CE distribution among LCCS nodes and sequencing of CE activation in standby groups to maximize the expected system connectivity over a specified mission time horizon. Optimization results are useful in guiding optimal decisions on reliable design and operation of LCCSs. Examples are provided to demonstrate application of the proposed methodology and optimization problem.

1. Introduction

Many real-world systems can be modeled as a linear consecutively connected system (LCCS), which is formed by a set of linearly ordered nodes with some of them containing one or multiple connection elements (CEs) [1,2]. A CE, when functioning, can provide a connection between its host node and a certain number of next nodes along the linear sequence depending on its connection range. The system is reliable if its source and destination nodes can be connected. The LCCS systems abound in applications such as sensor detection systems [3,4], flow transfer systems [3,5], and radio relay systems [6].

The LCCS model was first introduced by Hwang & Yao [7], which generalized consecutive-*k*-out-of-*n*: F system structures [1,2,5,8]. Refer to [9,10] for a research survey on consecutive-*k*-out-of-*n: F* and related systems. Methods for reliability analysis of binary and multi-state LCCSs were studied by researchers such as Hwang & Yao [7], Kossow & Preuss [11], Zuo & Liang [12,13] and Levitin [14]. The optimal CE allocation problem have also been formulated and solved for LCCSs with CEs of heterogeneous types (characterized by different lifetime distributions and connection ranges) [15,16]. It was shown that reliability of an LCCS can be considerably enhanced through optimally allocating heterogeneous CEs among system nodes [17,18].

Recently, horizon of LCCS research has been extended to consider phased-mission requirements, where different connection tasks involving different source and destination nodes are performed in different mission phases undergoing diverse stress levels and environment conditions [4,19]. Another extensions have been made to model and optimize LCCSs subject to certain gap constraints, particularly, LCCSs that can tolerate a certain number of gaps (disconnected nodes) [3], or a certain size of gap window [20], or both [21,22].

To the best of our knowledge, none of the existing works on LCCS modeling and optimization considered warm standby redundancy, a widely-applied fault tolerant technique for enhancing system reliability and availability while conserving limited system resources [23–25]. Warm standby is a system design in which one or multiple elements are on-line and working with one or more redundant elements serving as standby units. When an on-line element experiences a failure, it is removed from operation and replaced with a standby element (if available). There are two special cases of the warm standby redundancy techniques: hot and cold standby. Hot standby elements are synchronous with the online elements and ready to take over the mission at any time;

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Acronyms

cdf	cumulative distribution function
pdf	probability density function
GA	genetic algorithm
UGF	universal generating function (u-function)
LCCS	linear consecutively connected system
ILC	instantaneous LCCS connectivity
CE	connecting element
CEDSP	CE distribution and sequencing problem
DSCTP	discrete-state continuous-time process

Nomenclature

I	number of nodes that can contain CEs in the considered LCCS system
M	total number of CEs
N_j	number of CEs located at node j
$L_k(t)$	index of the most remote node that can be reached by operating CEs located at nodes 1,…,k at time t
$a(t)$	instantaneous LCCS connectivity
$A(T)$	expected LCCS connectivity over system mission time T
$s_i(k)$	index of CE that should be activated after the k-1th detected CE failure at node i
$G_i(t)$	random connection range at time t of group of CEs located at node i
$\mathbf{g}_i$	vector of possible connection ranges for group of CEs located at node i: $\mathbf{g}_i$={$g_{i,0}$, $g_{i,1}$,…,g_{i,N_i}}
$p_{i,k}(t)$	Pr($G_i(t)$=$g_{i,k}$), probability that group of CEs located at node i provides connection range $g_{i,k}$ at time t
T	mission time
$T_{i,k}$	random time when the last CE from sequence $s_i(1)$, …, $s_i(k)$ fails
$q_k(t)$	*pdf* of random value $T_{i,k}$
$F_{i,j}(t)$, $f_{i,j}(t)$	*cdf, pdf* of lifetime of CE j located at node i in the operation condition
$\omega_{i,j}$	nominal connection range of CE j located at node i
$\delta_{i,j}$	deceleration factor of CE j located at node i
η_j, β_j	scale, shape parameters of Weibull time-to-failure distribution for available CE j

they are exposed to the same operational environment and stresses compared with the online elements. Cold standby elements are unpowered and fully shielded from the operational stresses without consumption of energy and materials. However, a long restoration delay may be required when activating the cold standby elements. The general warm standby redundancy is a compromise between higher operation and maintenance cost in the hot standby and longer restoration delay in the cold standby. Motivated by practical applications explained in Section 2, in this work we advance the state-of-the-art by considering LCCSs with nodes containing heterogeneous warm standby CEs. Due to different characteristics of these CEs, node performance can change dynamically dependent on the type of CE that is online and operating. An iterative algorithm is first suggested for determining the discrete-state continuous-time process (DSCTP) characterizing the dynamic performance of node hosting a particular CE standby group. A universal generating function (UGF) technique is then used for assessing LCCS reliability indices including instantaneous and expected system connectivity.

Note that system dynamic behavior based on the DSCTP model and UGF technique has been addressed for multi-state systems in, e.g., [26–30]. Similar to the LCCS literature, these works did not consider warm standby redundancy. Moreover, time-to-failure of each system element was assumed to follow an exponential distribution, which allows using the Markov chain model. In this paper we make extensions to consider warm standby redundant structure composed of non-identical CEs with arbitrary types of time-to-failure distributions. Based on the suggested evaluation procedure, we make further contributions by identifying and solving an optimization problem of CE distribution and sequencing, which aims to find CE distribution among LCCS nodes as well as CE activation sequence within each standby group maximizing expected system connectivity over a specified mission time.

The remaining of this paper is organized as follows. Section 2 presents the LCCS model considered, definitions of system reliability indices (instantaneous and expected connectivity), and specific problems to be addressed. Section 3 presents an iterative algorithm for determining DSCTPs of particular CE standby groups. Section 4 presents the UGF technique used for evaluating the defined connectivity metrics, followed by an illustrative example in Section 5. Effects of CE arrangement and sequencing on system connectivity are demonstrated. Section 6 presents the genetic algorithm (GA) solution to the proposed optimization problem, followed by example optimization results in Section 7. Lastly, Section 8 concludes the work and gives directions of future research.

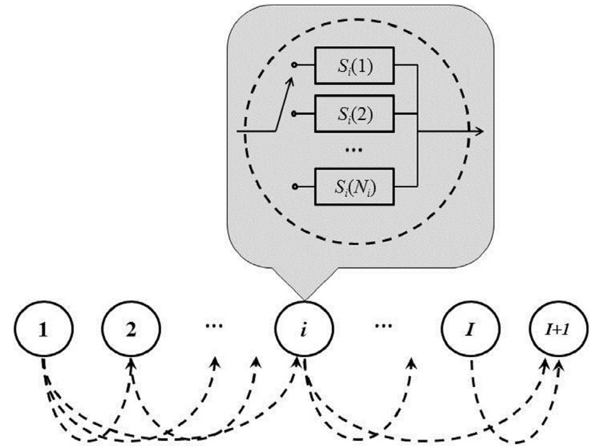

Fig. 1. Example of LCCS with 1-out-of-N_i warm standby groups.

2. LCCS model description and problem statement

The LCCS considered consists of $I+1$ consecutive nodes, as illustrated by an example in Fig. 1. Each node i (except the last node $I+1$) contains N_i binary state connecting elements (CEs) characterized by different connection ranges and time-to-failure distributions. The CEs located in the same node i compose a group, which is organized as a 1-out-of-N_i warm standby configuration with one CE being online and operating and the rest of the CEs being kept in a warm standby mode. If the online CE fails, based on a pre-specified sequence an available standby CE within the same group is activated to take over the task. Depending on the CE operating in the moment, the connection range of the group changes dynamically and discretely. Thus, the connection range $G_i(t)$ of each group i can be considered as a discrete-state continuous-time process (DSCTP). The system fails when node $I+1$ is disconnected from node 1.

An example of the considered LCCS is a set of radio relay stations (nodes) with a transmitter allocated at station 1 and a receiver allocated at station $I+1$. Each station i ($2\le i\le I$) can have a group of re-transmitters generating signals that reach the next $G_i(t)$ stations. Note that the connection range $G_i(t)$ depends on amplifier's power of re-transmitter which is online in station i at time t. The aim of the system is to provide signal propagation from the transmitter to the receiver.

Another example is a pipe flow transmission system with pump stations that provide pressure needed to transfer the flow to the next $G_i(t)$ stations [3]. Each station has a group of pumps composing a standby