Assessment of Wireless Smoke Alarm Interconnect Signal Delay on Safe Egress

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Abstract

Battery-powered smoke alarms with wireless interconnect signal transmission allow for retrofitting of homes with interconnected smoke alarms up to the current code-required installation locations without hardwiring. However, wireless communication draws additional current beyond basic smoke alarm operation and will affect battery life. To receive an interconnect signal, wireless smoke alarms must periodically power up the transceiver and listen for a transmitted signal from another alarm that initially responds to smoke. Naturally a question arises: what is an acceptable maximum delay time for wireless interconnected smoke alarms given the desire to extend battery life? The National Institute of Standard and Technology (NIST) conducted a Monte-Carlo computer fire model hazard assessment to quantify the relative effects of interconnect signal delay on the overall fire hazard in residential settings. The analysis considered the expected performance of smoke alarms satisfying ANSI/UL 217- 2015 fire and nuisance test requirements. Results are presented that show the effects of interconnect signal delay times on the probability of successful escape for scenarios where the interconnect signal was relevant to notification. These results may be used to balance a tradeoff between signal delay and maximizing battery life.

Introduction

Hardwired interconnected smoke alarms experience about 5 s to 10 s of delay on average between the local alarm and remote alarm audible emergency evacuation signal initiation. To achieve equal performance to hardwired interconnected alarms, wireless smoke alarm transceivers would need to be powered up and listening almost continuously, putting a huge strain on battery life. Currently, NFPA 72 specifies a maximum allowable response delay of 20 s from the activation of the local alarm to wireless interconnected signal reception and activation of remote alarms (29.10.8.2.3) [1]. In light of changes to ANSI/UL 217-2015 [2] with the addition of the performance requirements for new fire tests, an assessment of the impact of interconnect signal delay time is necessary to assess relative hazard. Scenarios relevant to occupant alerting from interconnected alarms remote from the fire would be the focus. In previous research conducted by NIST, an analysis methodology based on the Available Safe Egress Time (ASET) / Required Safe Egress Time (RSET) concept was used to estimate the relative performance of smoke alarms designed to alarm at specific smoke concentrations in flaming and smoldering polyurethane foam chair mock-up fires, Cleary [3]. The purpose was to provide guidance in selecting performance criteria for new smoldering and flaming polyurethane foam fire tests proposed for the Standard. Analysis was limited to 18 full-scale fire experiments conducted in a single small apartment-sized space. The analysis assumed smoke alarms (interconnected or not) alerted occupants upon reaching a certain ceiling smoke obscuration in the hallway between the master bedroom and the living room representing the responsive smoke alarm. Data was not available to account for responsive smoke alarms in all spaces that would be specified in the then current NFPA 72 installation requirements, i.e. bedrooms and living room, which were in all scenarios the location of the chair mockup fires. This performance bias is countered by the fact that many homes in the US still only have single station (non-interconnected) smoke alarm(s), and not installed in all locations per current requirements. Thus, the performance assessment in NIST Tech Note 1837 results in a performance level assessment between these bounding configurations.

The limitations in the full-scale experiments make assessment of wireless interconnect delay tenuous. So here, the recently-developed NIST Monte-Carlo hazard simulation method to assess residential fire safety designs (Reneke *et al*. [4]) is used to quantify the effect on safe egress of interconnect signal delay relative to a minimum delay of 5s to 10 s.

Modelling of Residential Fire Scenarios

A brief description of the Monte-Carlo method, building characteristics, fire scenarios and smoke alarm sensitivities developed in NIST Tech Note 2041 [4] and used in this study are described below, as are the assumed occupant characteristics and scenarios relevant to interconnect signal delay.

Monte-Carlo Method

The deterministic zone fire model CFAST [5] is used to compute the fire hazard development from individual fire scenarios. Given a configuration of rooms, the fire heat release rate, heat of combustion and yields of smoke and toxic gases, CFAST can predict the smoke obscuration, toxic gas and thermal (heat) fractional effective dose as a function of time in any room location at a specified height from the floor, thus ASET can be determined. Here, ASET was computed at a height from the floor of 1.5 m. A simple smoke alarm sub-model that specifies the smoke concentration (optical density) at alarm for a device located some small distance from the ceiling yields the smoke alarm activation time. RSET can be determined from the smoke alarm notification time and an estimate of occupant egress characteristics. In order to determine the expected performance impact of some change in a variable that could influence safe egress, many scenarios need to be explored. For instance, hazard development is a function of the room size(s) and the fire growth rate. Given the range of building configurations and fire growth rates possible, the expected performance is inherently probabilistic. In the Monte-Carlo Method here, samples are drawn from the various known probability distributions of relevant variables to generate the input conditions and the CFAST simulation is run using those input conditions. The process is repeated numerous times and the results aggregated to provide a probabilistic data set for analysis. Here and in NIST Tech Note 2041[4], approximately 50,000 CFAST simulations were run and analyzed. The relevant variables include building size, number and configuration of rooms, fire scenario and smoke alarm properties. Occupant characteristics are represented as a distribution of premovement and egress time, but they are not part of the sampled input variables for CFAST runs; the output results were integrated over the entire RSET distribution.

Building configurations

To determine building configurations, results from the US housing survey were used to gather the statistics on the number of rooms and the size of the US housing stock [4]. Room height is assumed to be 2.44 m. After sampling both the building size, number of bedrooms, total number of rooms, and specifying room sizes (minimum room size 1.9 m^2), connections between rooms are randomly assigned with a 50 % probability that any two rooms are connected. A check is then made to verify the configuration thus selected is feasible (i.e. a planar graph). The process is repeated until the desired number of floor plans is generated.

Fire scenarios

Fire scenarios include both flaming and smoldering upholstered furniture and flaming mattress fires. Data from Cleary [3] and Ohlemiller and Gann [6] were used to develop the distribution of fire growth rates and linear growth phase of items. Smoldering or flaming fire yields of smoke and toxic gases were constant for each burning mode. Details are provided in NIST Tech Note 2041 [4]. The room of fire origin (RFO) is randomly selected from the rooms in each configuration.

Smoke Alarm Properties

A statistical smoke alarm activation model for photoelectric and ionization alarms was developed for upholstered furniture containing polyurethane foam [7]. The statistical model is represented as a log-normal distribution with a geometric mean and geometric standard deviation. The specific distribution depends on the smoke alarm type, and the mode of combustion prior to alarm activation. The data used to develop the statistical model comes from NIST experiments measuring the response of a number of smoke alarms to the new smoldering and flaming polyurethane foam tests specified in ANSI/UL 217-2015. A total of 45 different alarm designs, representing alarms currently available in the U.S. (23 containing ionization sensors and 22 containing photoelectric sensors), were examined in the study. An estimate was made for the geometric mean and geometric standard deviation of the obscuration at alarm for flaming and smoldering upholstered furniture fires for new smoke alarms that would meet the ANSI/UL 217-2015 Standard. Note, the distributions are meant to represent the performance variation of many alarms for a particular fire scenario (flaming or smoldering) designed to meet the Standard. Table 1 give the means and standard deviations for ionization, photoelectric and new smoke alarms for flaming and smoldering upholstered furniture fires. For each CFAST run, an alarm obscuration is sampled from the (smoldering and/or flaming) probability distribution function, thus for a particular CFAST run, all smoke alarms would have the same obscuration limit. If a smoldering fire were to transition to flaming, the alarm obscuration limit would change from the smoldering to flaming value for the particular alarm.

Table 1. Parameters for smoke alarm statistical models

Alarm Type	Flaming Fire Obscuration		Smoldering Fire Obscuration	
	Geometric Mean (%/ft)	Geometric Std. Dev.	Geometric Mean (%/ft)	Geometric Std. Dev.
Ionization	2.1	1.3	10.0	1.2
Photoelectric	6.7	1.3	3.5	1.7
New Alarms*	3.0	1.3	5.0	1.3

*Alarms that would meet the new smoldering and flaming polyurethane foam tests specified in ANSI/UL 217-2015

Occupant characteristics

In NIST Tech Note 2041 [4] a fixed time was used to characterize the RSET for the scenarios. Here, the occupant characteristics include a responsive occupant capable of self-rescue and an RSET drawn from a distribution representing a range in premovement activities and travel distances modeled after the distributions in NIST Tech Note 1837 [3]. The premovement activities distribution here represents individual activities aggregated into a log-normal distribution (the same as the normal-responding, mobile occupants described in Tech Note 1837) with a median premovement time of 35 s and a geometric standard deviation of 1.6. Added to the premovement time distribution is a fixed time of 30 s representing the mean travel time during egress. ASET is computed at a fixed location where the occupant is initially located. For occupants initially located in the RFO, ASET is computed from conditions in that room until the required time to exit, a worst-case scenario.

ASET is based on exposure limits to toxic gases, heat and smoke obscuration. Toxic gases and heat exposure limits are defined by the fractional effective dose (FED) of either gases or heat at a conservative limit 0.3 evaluated at 1.5 m from the floor and computed using equations from ISO 13571:2012 [8]. A smoke obscuration limit of an optical density of 0.25 m^{-1} was specified, consistent with a value used in previous analysis [3,4].

Scenarios Relevant to Interconnect Signal Delay

In the following analysis, three scenarios were examined where egress could be impacted by interconnect signal delay, cases where an interconnected smoke alarm can alert an occupant who would not be initially alerted by the first responding alarm (i.e. the first smoke alarm responding to smoke stimuli). Thus, scenarios where the first responding smoke alarm was in a room occupied by a responsive occupant were ignored. Implicit in the scenarios examined is the assumption the responsive occupant is initially located in a room with an interconnected smoke alarm.

Case 1: The first case considered is where a smoke alarm located in the RFO provides the initial notification signal. The occupant in the connected room (i.e., a direct opening exists between RFO and the room in question) that reaches a FED or smoke limit first (worst case) will be considered. The smoke alarm in the room where the occupant is located can respond either to smoke or the interconnect signal. At least one room must be connected to the RFO for this case.

Case 2: The second case considered is where no smoke alarm is located in the RFO and a smoke alarm in a connected adjacent room provides the initial notification signal. Here the occupant considered is located in a room connected to the room with the initially responding alarm. The room with the responsive occupant is chosen to be the room that reaches a FED or smoke limit first (excluding the RFO and the room with the initially responding smoke alarm). The smoke alarm in the room where the occupant is located can respond either to smoke or the interconnect signal. At least two rooms must be connected to the RFO and themselves in this case.

Case 3: The third case is where a smoke alarm is in the RFO and an occupant not capable of self-rescue is present. The smoke alarm located in the RFO provides the initial notification signal. The responsive occupant in the connected room (opening between RFO and the room in question) that reaches a FED or smoke limit first (worst case) will be considered. The smoke alarm in the room where the responsive occupant is located can respond either to smoke or the interconnect signal. In this case RSET is computed for the responsive occupant, but ASET is computed for the occupant in the RFO that needs rescue. (Answering the question: does the responsive occupant have sufficient time to rescue the occupant in the RFO?) At least one room must be connected to the RFO for this case. A variant of the third case was examined where the smoke limit was not enforced in the RFO. The rationale for this variant is that if the responsive occupant does not experience smoke or tenability limits outside the RFO she/he is motivated and can affect a rescue upon reaching the RFO.

To perform the ASET/RSET analysis, the responsive occupant will have a specific RSET distribution for the particular CFAST run computed by summing the first responding alarm time, the interconnect signal delay of interest, and the RSET probability distribution. In runs where the interconnected smoke alarm responds to smoke prior to the interconnect signal, that alarm time replaces sum of the initial alarm time and the interconnect signal delay time. This resultant probability distribution is integrated from the minimum RSET time up to the time where ASET = RSET and the normalized fraction equals the fraction of successful escapes. This is repeated for interconnect signal delays from 0 to 120 s in 1 s increments.

Analysis of Results

Results are presented as the fraction of successful escapes versus the interconnect delay time for each of the cases and smoldering or flaming fires. Figure 1 shows the results for Case 1. While the analysis was performed primarily to assess new smoke alarms that would meet ANSI/UL 217-2015, results are also shown for ionization and photoelectric alarms. For the new alarms, the results show that even two min of interconnect delay time has a marginal effect on the fraction of successful escapes, which is nearly unity for both flaming and smoldering fires. The performance of ionization alarms with smoldering fires and photoelectric alarms with flaming fires is somewhat lower than the new alarm as expected.

Figure 2 shows the results for Case 2. As in Case 1, the new alarms results show that even two min of interconnect delay time has marginal effect on the fraction of successful escapes. Again, the performance of ionization alarms with smoldering fires and photoelectric alarms with flaming fires is lower than the new alarm results and lower than the corresponding results in Case 1.

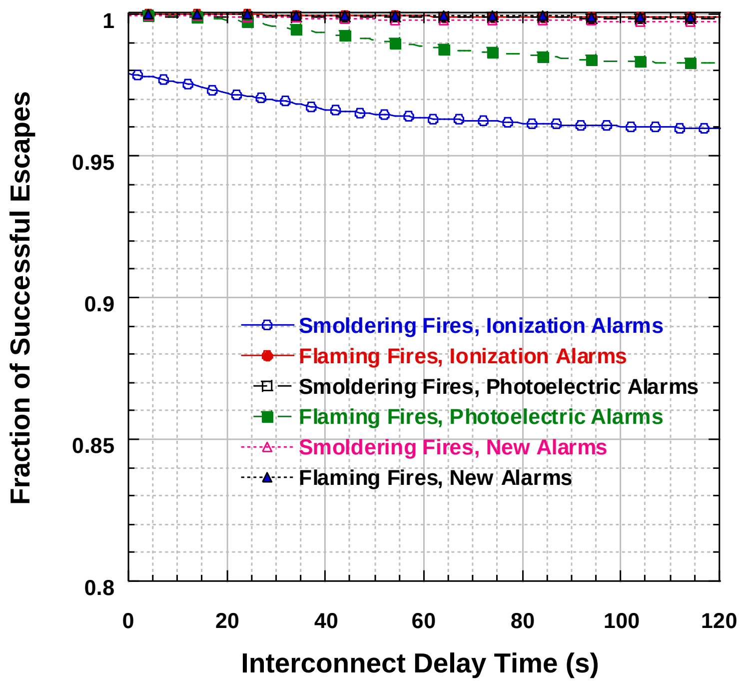

Figure 1. Case 1 - Smoke alarm in RFO and occupant of interest located outside RFO.

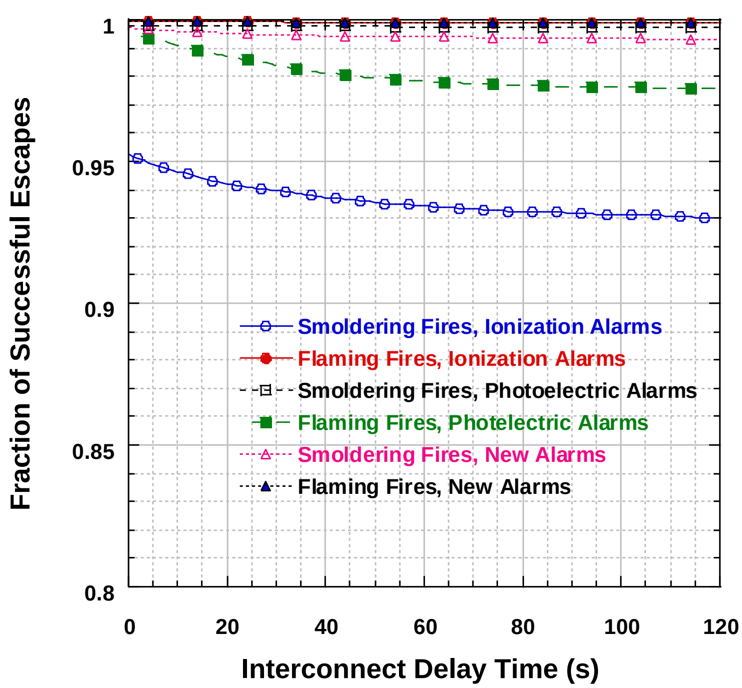

Figure 2. Case 2 – No smoke alarm in RFO and occupant of interest located outside RFO but not in room with the first responding smoke alarm.

Considering the first two cases, it would seem that interconnect delay time has a marginal effect up to at least 120 s, however smoke may be reaching the smoke alarm sooner than the interconnect delay time if that time is sufficiently long. Additionally, the occupant does not have to egress through a room with higher smoke concentration.

Figure 3 shows the results for Case 3. Only results for the new smoke alarms are shown. For smoldering fires there appears to be no effect on interconnect delay up to 120 s, while for flaming fires there is a decrease in the fraction of successful escapes from about 0.97 for no delay to below 0.4 for 120 s of delay. Results are shown for non-interconnected smoke alarms and flaming and smoldering fires. This emphasizes the benefit of interconnected alarms even with the new smoke alarms.

Figure 4 shows the results for the variant of Case 3 where the smoke limit is not enforced in the RFO compared to the when it is enforced. For flaming and smoldering fires interconnect signal delays up to 120 s have very little effect on the fraction of successful escapes for Case 3 when the smoke limit is not enforced in the RFO and the responsive occupant can rescue the occupant not capable of self-rescue.

Figure 5 shows the average of the three cases for the new detector. The average of the first three cases and the first two cases and the variant of Case 3 are presented. The fraction of successful escapes for the average of the first three cases decreases from about 0.99 to about 0.79 from 0 to 120 s of interconnect delay time for flaming fires.

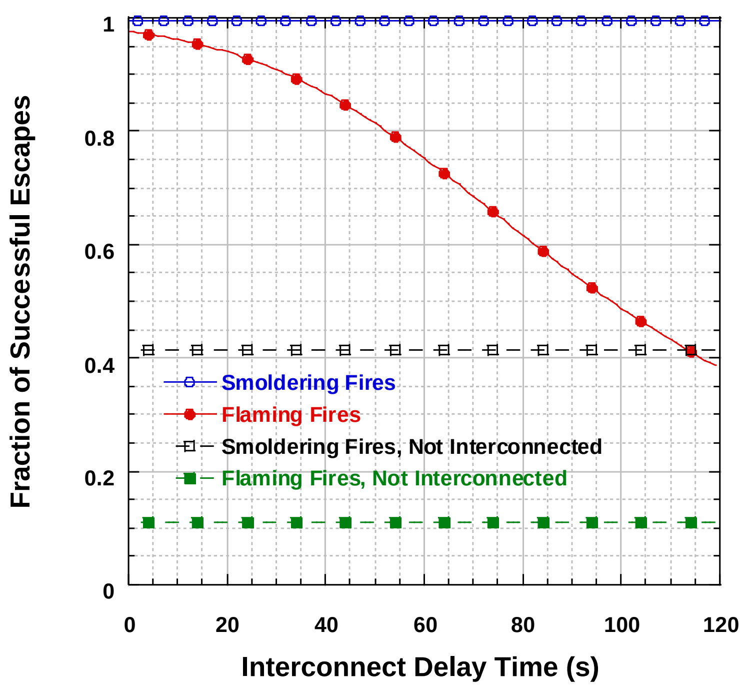

Figure 3. Case 3 - Smoke alarm located in RFO and occupant needing rescue located in RFO.

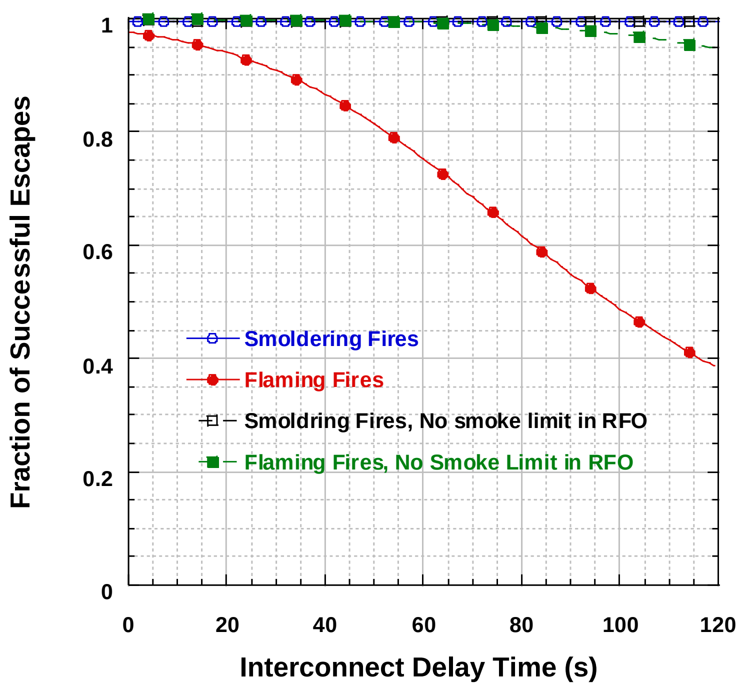

Figure 4. Comparison of results with and without a smoke limit in the RFO. Case 3 - Smoke alarm located in RFO and occupant needing rescue located in RFO.

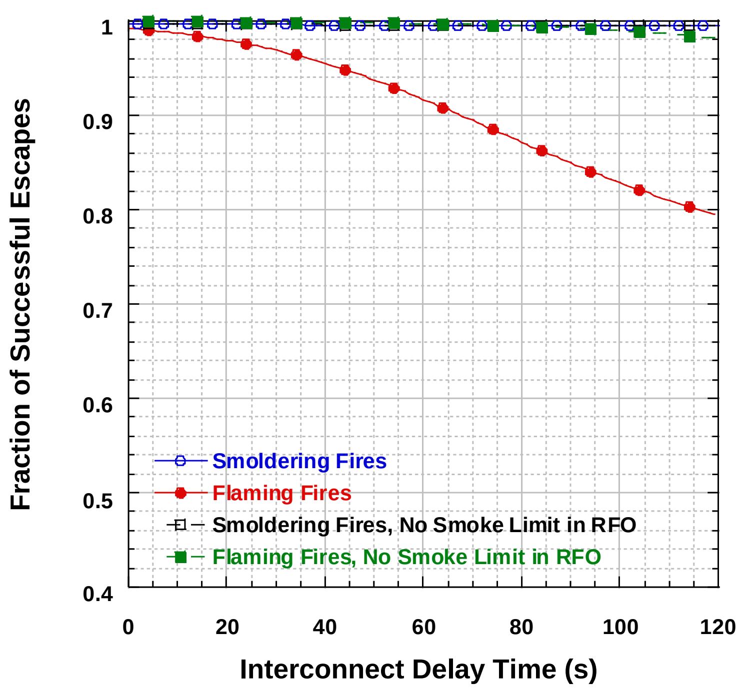

Figure 5. Average of cases 1-3 with and without the smoke limit in RFO.

Conclusions

The effect of interconnect signal delay time on the probability of successful escape was examined for cases where an occupant might be initially alerted from an alarm responding to an interconnect signal. The analysis focused on the outcome for new smoke alarms that would be subject to a new requirement on maximum interconnect signal delay. A recently-developed Monte-Carlo hazard assessment tool was used to provide a prediction of the probability of successful escape for the case of interest.

Results show that providing a full complement of interconnected smoke alarms yields a high probability of successful escape for the scenarios examined. The reduction in the probability of successful escape as the interconnect signal delay time is increased to 120 s is essentially limited to flaming fire scenarios where an occupant in the room of fire origin must be rescued. The conservative smoke limit drives this reduction.

Given that wireless interconnect signal transmission allows for affordable retrofitting of homes with interconnected smoke alarms up to the current code-required installation locations, it is natural to consider convenience and reliability to the consumer to maximize retrofitting. Extending battery life definitely increases consumer convenience and reliability. The analysis presented in this paper provides an initial guide into determining an acceptable balance between delay time for wireless interconnected smoke alarms and battery life.

References

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