Title:
Perceptually Adaptive Alarm Systems Using Doppler-Based Pitch Modulation

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Abstract

This technical note proposes a novel approach to auditory alarm systems using Doppler-based pitch modulation applied to existing alarm tones. By dynamically modulating pitch and amplitude, these systems provide intuitive, directionally meaningful cues to occupants and responders in emergency and clinical environments. This perceptual encoding leverages natural associations with motion and urgency, enabling faster, more accurate decision-making, even under stress or in sensory-restricted conditions. The system maintains compatibility with current alarm infrastructure while offering cross-domain applications, including fire safety, hospital monitoring, and inclusive evacuation guidance. This document establishes prior art for further research, development, and discussion.

1. Introduction

Imagine a visually impaired resident in a care home, unsure where to go. As the alarm's tone rises near one door and falls near another, they instinctively move toward safety — without needing sight, speech, or training.

Conventional alarm systems rely on loud, repetitive tones to attract attention. However, in high-stress or sensory-restrictive environments — such as fire, smoke, or crowded hospital wards — these static alerts can be overwhelming, indistinct, and insufficiently informative. This proposal introduces a perceptual alarm enhancement strategy using Doppler-like pitch modulation to embed meaning directly into existing alarm tones, aiding interpretation without requiring new sounds or retraining.

This builds upon prior research by **Cunningham and McGregor (2021)**, which demonstrated that Doppler-based pitch modulations influence listeners' perceptions of urgency, safety, proximity, and importance in controlled auditory alert studies. That foundational work supports the viability of perceptual encoding through pitch motion, but did not propose a specific system architecture or deployment strategy. The current proposal expands on these findings by outlining a functional design framework for implementation in real-world settings.

2. Concept Overview

The system modulates existing alarm tones with pitch and amplitude changes that simulate Doppler effects. These modulations provide embedded cues based on urgency, proximity, and directionality:

- **Upward shift (Doppler up):** Indicates increasing danger or priority through a perceptible rise in pitch and amplitude
- **Stable signal (neutral):** Indicates a monitored or passive state, with minimal pitch and amplitude variation
- **Downward shift (Doppler down):** Suggests a safe path or stabilising condition through a perceptible decrease in pitch and amplitude

This modulation can occur cyclically or be triggered dynamically by sensor data (e.g. temperature, motion, heart rate), creating an interactive, perceptually rich auditory layer.

3. Use in Fire Alarm Systems

In fire scenarios, the system helps evacuees differentiate between routes:

- Alarms near active hazards produce upward shifts
- Safe exits emit downward shifts
- Non-critical zones remain stable

As individuals move, the interaction between their own velocity and pitch trajectory enhances intuitive understanding. The result is a responsive audio map that can guide untrained occupants to safety, even in visually limited conditions.

4. Adapting Clinical Alarm Environments

In clinical settings with numerous identical alarms, this system can reduce alarm fatigue and support fast triage:

- **Upward shift:** patient requires immediate assistance
- **Stable signal:** monitor
- **Downward shift:** stable or resolved condition

This enables healthcare staff to prioritise without manually verifying each machine, supporting safer, calmer environments.

5. Firefighters and First Responders

Trained personnel can learn to interpret these signals in reverse:

- **Upward shift** = heading toward the hazard (e.g. fire origin)
- **Downward shift** = moving away

This provides real-time hazard localisation without additional equipment and can enhance response efficiency in complex or obscured conditions.

6. Drill Mode Functionality

The system supports a 'drill mode' configuration for training exercises. In this mode, pitch shifts can be selectively applied — such as emitting only downward shifts near fire exits — while keeping other alarms stable. This allows for spatial learning and orientation without triggering widespread urgency or alarm fatigue. It ensures drills remain distinct from live alerts while still benefiting from the perceptual cues inherent in the system.

7. Cognitive and Perceptual Basis

- **Auditory attention theory**: The brain prioritises change (pitch, amplitude) over constancy
- **Doppler familiarity**: Culturally reinforced by sirens and moving vehicles
- **Lower SPL efficacy**: Salience is achieved through modulation, reducing the need for high volume
- **Embodied interpretation**: Listeners instinctively map pitch change to movement and risk

Rising Doppler shifts also generate a biologically ingrained sense of threat or urgency, as they mimic approaching movement in space. This perceptual cue is difficult to ignore or habituate to, even at moderate volume levels. As a result, alarms with upward modulation are more likely to trigger appropriate behavioural responses, especially in contrast to static tones that people may learn to dismiss as drills or background noise. Additionally, the dynamic variation in pitch and amplitude increases the salience of alarms at distance, making them more likely to be detected early in larger or open-plan spaces compared to unmodulated tones.

8. Feasibility Considerations

The system can be implemented incrementally using existing infrastructure. In its simplest form, perceptual modulation can be overlaid onto current alarm tones via firmware updates or low-cost DSP modules. Sensor integration is achievable through standard building management system (BMS) interfaces, and digital decoding of watermark signals can be performed via mobile apps or smart assistant devices using common microphones. Modulation parameters can be designed to survive typical phone audio compression, ensuring remote decoding is robust.

Pilot trials could begin in small-scale, acoustically controlled environments such as care homes, clinics, or residential campuses where alarm confusion or inaccessibility has clear implications. Regulatory compliance can be preserved by maintaining core alert tone structures and ensuring modulation does not interfere with required signal recognition standards.

A reference implementation could involve a layered audio processing chain where sensor inputs control real-time pitch and amplitude shifts. These shifts would be applied relative to the base tone of the existing alarm: for example, an upward shift could correspond to a +20% increase in frequency over 1 second, and a perceptually adaptive gain increase, with levels suitable to overcome ambient masking and support perceptual urgency under varying environmental conditions. Watermark signals for sensor identification could be encoded at regular intervals using minor modulations or structured pulse contours, without affecting core alarm recognisability.

9. Regulatory and Standards Alignment

The proposed system is designed to operate using pitch and amplitude modulation of existing alarm tones rather than replacing them. As such, it can be implemented in parallel with current standards including:

- **EN 54** (EU fire alarm systems)
- **NFPA 72** (US National Fire Alarm and Signaling Code)
- **IEC 60601-1-8** (Medical electrical equipment alarm signals)

Because the core tone structure remains identifiable and functionally unchanged, the perceptual enhancements can be added as an overlaid cue layer without violating regulatory compliance.

10. Environmental Interaction and Navigation

As Doppler-shifted tones reflect and scatter in space, listeners gain subtle cues about occlusions, object sizes, and spatial layouts. These reflections change in character as pitch shifts occur, enabling individuals to detect obstacles and spatial boundaries. Additionally, when alarms are partially or fully occluded by doors, walls, or furnishings, the perceptual modulation of pitch and amplitude remains more distinguishable than a static tone. This allows users to make more accurate judgments about the location, urgency, and state of occluded alarms, helping them avoid hazards or choose safe paths even without direct visual cues.

The system may also enhance awareness of hazards behind closed doors. If an area behind a door contains heat or smoke and is actively triggering sensors, the emitted alarm will have an upward shift, while unaffected or safer areas emit stable or downward shifts. This provides an intuitive auditory cue about what lies beyond the listener’s current view, improving situational awareness and helping to prevent accidental exposure to fire or smoke.

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11. Benefits

- Improves clarity in multi-alarm environments
- Enhances directionality and urgency perception
- Reduces auditory overload and panic
- Requires no new sounds or training
- Enables bidirectional use (evacuees and responders)
- Compatible with existing systems

- Supports safe, clear training drills
- Reduces need for excessively high sound pressure levels, lowering risk of temporary threshold shift and long-term hearing damage
- More resistant to auditory masking than static tones due to pitch variation
- Likely to be more perceptible for individuals with hearing impairments due to emphasis on motion-based cues
- Improves awareness of risks behind closed doors through pitch cues
- Actively supports real-time path decision-making during evacuation, enabling people to choose safer exits by interpreting pitch cues, even in unfamiliar or visually obstructed environments
- Enables perceptual triage by allowing users to prioritise alarms based on pitch and amplitude motion, reducing cognitive overload in multi-alarm environments
- Builds trust in alarm systems by providing clear, varied, and context-sensitive feedback, reducing habituation and promoting appropriate action
- Scales naturally from single-room systems to full-building deployments without requiring new tones, enabling flexible integration with existing infrastructure
- Enhances shared situational awareness in public and institutional spaces by conveying consistent auditory meaning to all listeners, regardless of location or visibility

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12. Future Enhancements

A potential extension of this system involves embedding unique, digitally encoded modulation patterns — perceptual watermarks — into each alarm signal. These structured modulations would allow alarms to carry sensor-specific identifiers that can be interpreted by digital tools, without requiring cognitive parsing by the listener. Such identifiers could enable:

- Real-time localisation of alarms by responders using audio alone
- Mapping triggered alarms to specific sensors or zones within a building
- Integration with systems like what3words or coordinate mapping, potentially enhanced with altitude encoding via pitch offsets
- Cross-checking of alarm states in large-scale buildings, campuses, or multi-floor environments without visual confirmation

Modulation rate, depth, and contour could also be dynamically shaped by sensor type and signal intensity. For example, rapid temperature rise or dense smoke could produce faster or sharper upward shifts, allowing the perceptual signal to reflect not just the presence of danger, but its severity and acceleration. This would provide a graded sense of urgency based on real-time environmental conditions, enhancing situational awareness for both evacuees and responders.

The system could also support vulnerable individuals by enabling remote location identification through common devices. For example, a person could place a phone call and hold their device near an active alarm. Remote software could decode the modulation patterns received through the microphone, identifying the originating sensor(s) and inferring the caller's location. This allows non-verbal or visually impaired users to communicate their position without needing to describe or navigate their surroundings.

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13. Conclusion

This proposal is grounded not only in perceptual and technical innovation, but also in the belief that emergency systems should work intuitively for everyone, particularly under stress or in unfamiliar spaces. The suitability of this approach lies in its alignment with existing infrastructure, its adaptability to varied environments, and its potential to assist vulnerable users without imposing cognitive or auditory burden. These features are not introduced as breakthroughs in themselves, but as a response to longstanding gaps in accessibility, spatial awareness, and trust in alarm systems. The intention is to offer a model that may inform future systems, be adapted to local needs, or inspire new implementations.

It is shared to establish prior art and stimulate further research, testing, and potential implementation. By embedding directional, urgency-related, and navigational cues into familiar alarm tones, this approach offers clear benefits for emergency response, healthcare safety, and accessibility-focused environments. I welcome contact from researchers, safety specialists, and accessibility designers interested in exploring this concept further.

Licensing and Citation

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Reference

Cunningham, S., & McGregor, I. (2021). *Evaluating Use of the Doppler Effect to Enhance Auditory Alerts*. International Journal of Human–Computer Interaction, 37(11), 1074–1087. https://doi.org/10.1080/10447318.2020.1870818