

Why (Special Agent) Johnny (Still) Can't Encrypt: A Security Analysis of the APCO Project 25 Two-Way Radio System

Sandy Clark Travis Goodspeed Perry Metzger Zachary Wasserman Kevin Xu
Matt Blaze
University of Pennsylvania

APCO Project 25 (“P25”) is a suite of wireless communications protocols used in the US and elsewhere for public safety two-way (voice) radio systems. The protocols include security options in which voice and data traffic can be cryptographically protected from eavesdropping. This paper analyzes the security of P25 systems against both passive and active adversaries. We found a number of protocol, implementation, and user interface weaknesses that routinely leak information to a passive eavesdropper or that permit highly efficient and difficult to detect active attacks. We introduce new *selective subframe jamming* attacks against P25, in which an active attacker with very modest resources can prevent specific kinds of traffic (such as encrypted messages) from being received, while emitting only a small fraction of the aggregate power of the legitimate transmitter. We also found that even the passive attacks represent a serious practical threat. In a study we conducted over a two year period in several US metropolitan areas, we found that a significant fraction of the “encrypted” P25 tactical radio traffic sent by federal law enforcement surveillance operatives is actually sent in the clear, in spite of their users’ belief that they are encrypted, and often reveals such sensitive data as the names of informants in criminal investigations.

1 Introduction

APCO Project 25 [16] (also called “P25”) is a suite of digital protocols and standards designed for use in narrowband short-range (VHF and UHF) land-mobile wireless two-way communications systems. The system is intended primarily for use by public safety and other government users.

The P25 protocols are designed by an international consortium of vendors and users (centered in the United

States), coordinated by the Association of Public Safety Communications Officers (APCO) and with its standards documents published by the Telecommunications Industry Association (TIA). Work on the protocols started in 1989, with new protocol features continuing to be refined and standardized on an ongoing basis.

The P25 protocols support both digital voice and low bit-rate data messaging, and are designed to operate in stand-alone short range “point-to-point” configurations or with the aid of infrastructure such as repeaters that can cover larger metropolitan and regional areas.

P25 supports a number of security features, including optional encryption of voice and data, based on either manual keying of mobile stations or “over the air” rekeying (“OTAR” [15]) through a key distribution center.

In this paper, we examine the security of the P25 (and common implementations of it) against unauthorized eavesdropping, passive and active traffic analysis, and denial-of-service through selective jamming.

This paper has three main contributions: First, we give an (informal) analysis of the P25 security protocols and standard implementations. We identify a number of limitations and weaknesses of the security properties of the protocol against various adversaries as well as ambiguities in the standard usage model and user interface that make ostensibly encrypted traffic vulnerable to unintended and undetected transmission of cleartext. We also discovered an implementation error, apparently common to virtually every current P25 product, that leaks station identification information in the clear even when in encrypted mode.

Next, we describe a range of practical active attacks against the P25 protocols that can selectively deny service or leak location information about users. In particular, we introduce a new active denial-of-service attack, *selective subframe jamming*, that requires *more than an*

order of magnitude less average power to effectively jam P25 traffic than the analog systems they are intended to replace. These attacks, which are difficult for the end-user to identify, can be targeted against encrypted traffic (thereby forcing the users to disable encryption), or can be used to deny service altogether. The attack can be implemented in very simple and inexpensive hardware. We implemented a complete receiver and exciter for an effective P25 jammer by installing custom firmware in a \$15 toy “instant messenger” device marketed to pre-teen children.

Finally, we show that unintended transmission of cleartext commonly occurs in practice, even among trained users engaging in sensitive communication. We analyzed the over-the-air P25 traffic from the secure two-way radio systems used by federal law enforcement agencies in several metropolitan areas over a two year period and found that a significant fraction of highly sensitive “encrypted” communication is actually sent in the clear, without detection by the users.

2 P25 Overview

P25 systems are intended as an evolutionary replacement for the two-way radio systems used by local public safety agencies and national law enforcement and intelligence services. Historically, these systems have used analog narrowband FM modulation. Users (or their vehicles) typically carry mobile transceivers¹ that receive voice communications from other users, with all radios in a group monitoring a common broadcast channel. P25 was designed to be deployed without significant change to the user experience, radio channel assignments, spectrum bandwidth used, or network topology of the legacy analog two-way radio systems they replace, but adding several features made possible by the use of digital modulation, such as encryption.

Mobile stations (in both P25 and legacy analog) are equipped with “Push-To-Talk” buttons; the systems are half duplex, with at most one user transmitting on a given channel at a time. The radios typically either constantly receive on a single assigned channel or scan among multiple channels. P25 radios can be configured to mute received traffic not intended for them, and will ignore received encrypted traffic for which a correct decryption key is not available.

P25 mobile terminal and infrastructure equipment is manufactured and marketed in the United States by

¹Various radio models are designed be installed permanently in vehicles or carried as portable battery-powered “walkie-talkies”.



Figure 1: Motorola XTS5000 Handheld P25 Radio

a number of vendors, including E.F. Johnson, Harris, Icom, Motorola, RELM Wireless and Thales/Racal, among others. The P25 standards employ a number of patented technologies, including the voice codec, called IMBE [17]. Cross-licensing of patents and other technology is standard practice among the P25 equipment vendors, resulting in various features and implementation details common among equipment produced by different manufacturers. Motorola is perhaps the dominant U.S. vendor, and in this paper, we use Motorola’s P25 product line to illustrate features, user interfaces, and attack scenarios. A typical P25 handheld radio is shown in Figure 1.

For compatibility with existing analog FM based radio systems and for consistency with current radio spectrum allocation practices, P25 radios use discrete narrowband radio channels (and not the spread spectrum techniques normally associated with digital wireless communication).

Current P25 radio channels occupy a standard 12.5 KHz “slot” of bandwidth in the VHF or UHF land mobile radio spectrum. P25 uses the same channel allocations as existing legacy narrowband analog FM two-way radios. To facilitate a gradual transition to the system, P25-compliant radios must be capable of demodulating legacy analog transmissions, though legacy analog radios cannot, of course, demodulate P25 transmissions.

In the current P25 digital modulation scheme, called C4FM, the 12.5kHz channel is used to transmit a four-level signal, sending two bits with each symbol at a

rate of 4800 symbols per second, for a total bit rate of 9600bps.²

P25 radio systems can be configured for three different network topologies, depending on varying degrees of infrastructural support in the area of coverage:

- *Simplex* configuration: All group members set transmitters and receiver to receive and broadcast on the same frequency. The range of a simplex system is the area over which each station’s transmissions can be received directly by the other stations, which is limited by terrain, power level, and interference from co-channel users.
- *Repeater* operation: Mobile stations transmit on one frequency to a fixed-location repeater, which in turn retransmits communications on a second frequency received by all the mobiles in a group. Repeater configurations thus use two frequencies per channel. The repeater typically possesses both an advantageous geographical location and access to electrical power. Repeaters extend the effective range of a system by rebroadcasting mobile transmissions at higher power and from a greater height
- *Trunking*: Mobile stations transmit and receive on a variety of frequencies as orchestrated by a “control channel” supported by a network of base stations. By dynamically allocating transmit and receive frequencies from among a set of allocated channels, scarce radio bandwidth may be effectively time and frequency domain multiplexed among multiple groups of users.

For simplicity, this paper focuses chiefly on weaknesses and attacks that apply to all three configurations.

As P25 is a digital protocol, it is technically straightforward to encrypt voice and data traffic, something that was far more difficult in the analog domain systems it is designed to replace. However, P25 encryption is an optional feature, and even radios equipped for encryption still have the capability to operate in the clear mode. Keys may be manually loaded into mobile units or may be updated at intervals using the OTAR protocol.

P25 also provides for a low-bandwidth data stream that piggybacks atop voice communications, and for a higher bandwidth data transmission mode in which data

²This 12.5 KHz “Phase 1” modulation scheme is designed to co-exist with analog legacy systems. P25 also specifies a quadrature phase shift keying and TDMA and FMDA schemes that uses only 6.25kHz of spectrum. These P25 “Phase 2” modulation systems have not yet been widely deployed, but in any case do not affect the security analysis in this paper.

is sent independent of voice. (It is this facility which enables the OTAR protocol, as well as attacks we describe below to actively locate mobile users.)

2.1 The P25 Protocols

This section is a brief overview of the most salient features of the P25 protocols relevant to rest of this paper. The P25 protocols are quite complex, and the reader is urged to consult the standards themselves for a complete description of the various data formats, options, and message flows. An excellent overview of the most important P25 protocol features can be found in reference [6].

The P25 Phase 1 (the currently deployed version) RF-layer protocol uses a four level code over a 12.5kHz channel, sending two bits per transmitted symbol at 4800 symbols per second or 9600 bits per second.

A typical transmission consists of a series of *frames*, transmitted back-to-back in sequence. The start of each frame is identified by a special 24 symbol (48 bit) frame synchronization pattern.

This is immediately followed by a 64 bit field containing 16 bits of information and 48 bits of error correction. 12 bits, the *NAC* field, identify the network on which the message is being sent – a radio remains muted unless a received transmission contains the correct NAC, which prevents unintended interference by distinct networks using the same set of frequencies. 4 bits, the *DUID* field, identify the type of the frame. Either a voice header, a voice *superframe*, a voice trailer, a data packet, or a trunked frame. All frames but the packet data frames are of fixed length.

Header frames contain a 16 bit field designating the destination talk group *TGID* for which a transmission is intended. This permits radios to mute transmissions not intended for them. The header also contains information for use in encrypted communications, specifically an initialization vector (designated the *Message Indicator* or *MI* in P25, which is 72 bits wide but effectively only 64 bits), an eight bit Algorithm ID, and a 16 bit Key ID. Transmissions in the clear set these fields to all zeros. This information is also accompanied by a large number of error correction bits.

The actual audio payload, encoded as IMBE voice subframes, is sent inside *Link Data Units (LDUs)*. A voice LDU contains a header followed by a sequence of nine 144 bit IMBE voice subframes (each of which encodes 20ms of audio, for a total 180ms of encoded audio in each LDU frame), plus additional metadata and a small amount of piggybacked low speed data. Each LDU, including headers, metadata, voice subframes, and

Header Data Unit	Logical Link Data Unit 1	Logical Link Data Unit 2	Logical Link Data Unit 1	Logical Link Data Unit 2	Terminator Data Unit
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Figure 2: P25 Voice Transmission Framing (from Project 25 FDMA - Common Air Interface: TIA-102.BAAA-A)

error correction is 864 symbols (1728 bits) long.

A voice transmission thus consists of a header frame followed by an arbitrary length alternating sequence of LDU frames in two slightly different formats (called LDU1 and LDU2 frames, which differ in the metadata they carry), followed by a terminator frame. See Figure 2. Note that the number of voice LDU1 and LDU2 frames to be sent in a transmission is not generally known at the start of the transmission, since it depends on how long the user speaks.

LDU1 frames contain the source unit ID of a given radio (a 24 bit field), and either a 24 bit destination unit ID (for point to point transmissions) or a 16 bit TGID (for group transmissions).

LDU2 frames contain new MI, Algorithm ID and Key ID fields. Voice LDU frames alternate between the LDU1 and LDU2 format. Because all the metadata required to recognize a transmission is available over the course of two LDU frames, a receiver can use an LDU1/LDU2 pair (also called a “superframe”), to “catch up with” a transmission even if the initial transmission header was missed.

See Figure 3 for the structure of the LDU1 and LDU2 frames.

Terminator units, which may follow either an LDU1 or LDU2 frame, indicate the end of a transmission.

A separate format exists for (non-voice) packet data frames. Data frames may optionally request acknowledgement to permit immediate retransmission in case of corruption. A header, which is always unencrypted, indicates which unit ID has originated the packet or is its target. (These features will prove important in the discussion of active radio localization attacks.)

Trunking systems also use a frame type of their own on their control channel. (We do not discuss the details of this frame type, as they are not relevant to our study.)

It is important to note a detail of the error correction codes used for the voice data in LDU1 and LDU2 frames. The IMBE codec has the feature that not all bits in the encoded representation are of equal importance in regenerating the original transmitted speech. To reduce the amount of error correction needed in the frame, bits that contribute more to intelligibility receive more error correction than those that contribute less, with the least important bits receiving no error correction at all. Although

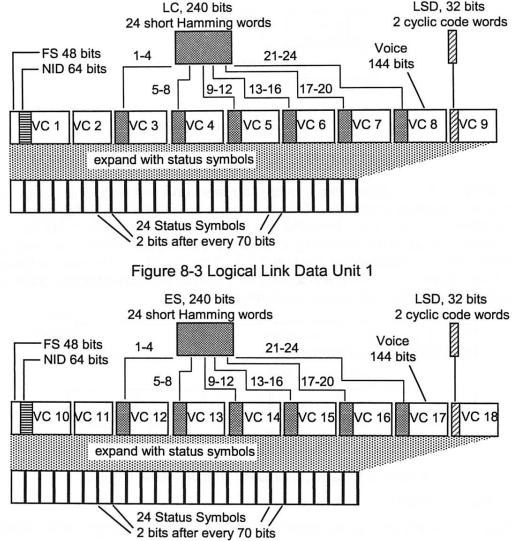


Figure 2: P25 Voice Transmission Framing

Figure 3: Logical Data Unit structure (from Project 25 FDMA - Common Air Interface: TIA-102.BAAA-A)

this means that the encoding of voice over the air is more efficient, it also means that voice transmissions are not protected by with block ciphers or message authentication codes, as we explain below.

2.2 Security Features

P25 provides options for traffic confidentiality using symmetric-key ciphers, which can be implemented in software or hardware. The standard supports mass-market “Type 2/3/4” crypto engines (such as DES and AES) for unclassified domestic and export users, as well as NSA-approved “Type 1” cryptography for government classified traffic. (The use of Type 1 hardware is tightly controlled and restricted to classified traffic only; even sensitive criminal law enforcement surveillance operations typically must use commercial Type 2/3/4 cryptography.)

The DES, 3DES and AES ciphers are specified in the standard, in addition to the null cipher for cleartext. The standard also provides for the use of vendor-specific proprietary algorithms (such as 40 bit RC4 for radios aimed at the export market). [13]

At least for unclassified Type 2, 3 and 4 cryptography, pre-shared symmetric keys are used for all traffic encryption. The system requires a key table located in each radio mapping unique *Key ID+Algorithm ID* tuples to particular symmetric cipher keys stored within the unit. This table may be keyed manually or with the use of an Over The Air Rekeying protocol. A group of radios can communicate in encrypted mode only if all radios share a common key (labeled with the same Key ID).

Many message frame types contain a tuple consisting of an initialization vector (the MI), a Key ID and an Algorithm ID. A clear transmission is indicated by a zero MI and KID and a special ALGID. The key used by a given radio group may thus change from message to message and even from frame to frame (some frames may be sent encrypted while others are sent in the clear).

Because of the above-described property of the error correction mechanisms used, especially in voice frames such as the LDU1 and LDU2 frame types, there is no mechanism to detect errors in certain portions of transmitted frames. This was a deliberate design choice, to permit undetected corruption of portions of the frame that are less important for intelligibility.

This error-tolerant design means that standard block cipher modes (such as Cipher Block Chaining) cannot be used for voice encryption; block ciphers require the accurate reception of an entire block in order for any portion of the block to be correctly decrypted. P25 voice encryption is specified stream ciphers, in which a cryptographic keystream generator produces a pseudorandom bit sequence that is XORed with the data stream to encrypt (on the transmit side) and decrypt (on the receive side). In order to permit conventional block ciphers (including DES and AES) to be used as stream ciphers, they are run in Output Feedback mode (“OFB”) in order to generate a keystream. (Some native stream ciphers, such as RC4, have also been implemented by some manufacturers, particularly for use in export radios that limited to short key lengths.)

For the same reason – received frames must tolerate the presence of some bit errors – cryptographic message authentication codes (“MACs”), which fail if any bit errors whatsoever are present, are not used.³

3 Security Deficiencies

In the previous section, we described a highly ad hoc, constrained architecture that, we note, departs in significant ways from conservative security design, does not provide clean separation of layers, and lacks a clearly stated set of requirements against which it can be tested.

This is true even in portions of the architecture, such as the packet data frame subsystem, which are at least in theory compatible with well understood standard cryptographic protocols, such as those based on block ciphers and MACs.

This ad hoc design might by itself represent a security concern. In fact, the design introduces significant certificational weaknesses in the cryptographic protection provided.

But such weaknesses do not, in and of themselves, automatically result in exploitable vulnerabilities. However, they weaken and complicate the guarantees that can be made to higher layers of the system. Given the overall complexity of the P25 protocol suite, and especially given the reliance of upper layers such as the OTAR subsystem on the behavior of lower layers, such deficiencies make the security of the overall system much harder for a defender to analyze.

The P25 implementation and user interfaces, too, suffer from an ad hoc design that, we shall see, does not fare well against an adversarial threat. There is no evidence in the standards documents, product literature, or other documentation of user interface or usability requirements, or of testing procedures such as “red team” exercises or user behavior studies.

As we shall see later in this paper, taken in combination, the design weaknesses of the P25 security architecture and the standard implementations of it admit practical, exploitable vulnerabilities that routinely leak sensitive traffic and that allow an active attacker remarkable leverage.

At the root of many of the most important practical vulnerabilities in P25 systems are a number of fundamentally weak cryptographic, security protocol, and coding design choices.

3.1 Authentication and Error Correction

A well known weakness of stream ciphers is that attackers who know the plaintext content of any encrypted portion of transmission may make arbitrary changes to that content at will simply by flipping appropriate bits in the data stream. For this reason, it is usually recommended that stream ciphers be used in conjunction with MACs. But the same design decision (error tolerance) that forced the use of stream ciphers in P25 also precludes the use of MACs.

Because no MACs are employed on voice and most

³Some vendors support AES in GCM mode, but it is not standardized. In any case, even when GCM mode is used, it does not authenticate the voice traffic as originating with a particular user.

other traffic, even in encrypted mode, it is trivial for an adversary to masquerade as a legitimate user, to inject false voice traffic, and to replay captured traffic, even when all radios in a system have encryption configured and enabled.

The ability for an adversary to inject false traffic without detection is, of course, a fundamental weakness by itself, but also something that can serve as a stepping stone to more sophisticated attacks (as we shall see later).

A related issue is that because the P25 voice mode is real time, it relies entirely on error correction (rather than detection and retransmission) for integrity. The error correction scheme in the P25 frame is highly optimized for the various kinds of content in the frame. In particular, a single error correcting code is not used across the entire frame. Instead, different sections of P25 frames are error corrected in independent ways, with separate codes providing error correction for relatively small individual portions of the data stream. This design leaves the frames vulnerable to highly efficient active jamming attacks that target small-but-critical subframes, as we will see in Section 4.

3.2 Unencrypted Metadata

Even when encryption is used, much of the basic metadata that identifies the systems, talk groups, sender and receiver user IDs, and message types of transmissions are sent in the clear and are directly available to a passive eavesdropper for traffic analysis and to facilitate other attacks. While some of these fields can be optionally encrypted (the use of encryption is not tied to whether voice encryption is enabled), others must always be sent in the clear due to the basic architecture of P25 networks.

For example, the start of every frame of every transmission includes a *Network Identifier* (“NID”) field that contains the 12 bit Network Access Code (NAC) and the 4 bit frame type (“Data Unit ID”). The NAC code identifies the network on which the transmission is being sent; on frequencies that carry traffic from multiple networks, it effectively identifies the organization or agency from which a transmission originated. The Data Unit ID identifies the type of traffic, voice, packet data, etc. Several aspects of the P25 architecture requires that the NID be sent in the clear. For example, repeaters and other infrastructure (which do not have access to keying material) use it to control the processing of the traffic they receive. The effect is that the NAC and type of transmission is available to a passive adversary on every transmission.

For voice traffic, a *Link Control Word* (“LCW”) is included in every other LDU voice frame (specifically, in

the LDU1 frames). The LCW includes the transmitter’s unique unit ID (somewhat confusingly called the “Link IDs” in various places in the standard). The ID fields in the LCW can be optionally encrypted, but whether they are actually encrypted is not intrinsically tied to whether encryption is enabled for the voice content itself (rather it is indicated by a “protected” bit flag in the LCW).

Worse, we discovered a widely deployed implementation error that exacerbates the unit ID information leaked in the LCW. We examined the transmitted bitstream generated by Motorola P25 radios in our laboratory, and also the over-the-air tactical P25 traffic on the frequencies used by Federal law enforcement agencies in several US metropolitan areas (captured over a period of more than one year)

We found that in every P25 transmission we captured, both in P25 transmissions sent from our equipment and from encrypted traffic we intercepted over the air, the LCW protection bit is never set; the option to encrypt the LCW does not appear ever to be enabled, even when the voice traffic itself is encrypted. That is, in both Motorola’s XTS5000 product and, apparently, in virtually every other P25 radio in current use by the Federal government, the sender’s Unit Link ID is always sent in the clear, even for encrypted traffic. This, of course, greatly facilitates traffic analysis of encrypted networks by a passive adversary, who can simply record the unique identifiers of each transmission as it comes in. It also simplifies certain active attacks we discuss in the section below.

3.3 Traffic Analysis and Active Location Tracking

Generally, a radio’s location may be tracked only if it is actively transmitting. Standard direction finding techniques can locate a transmitting radio relatively quickly [12, 10]. P25 provides a convenient means for an attacker to induce otherwise silent radios to transmit, permitting active continuous tracking of a radio’s user.

The P25 protocol includes a data packet transmission subsystem (this is separate from the streaming real-time digital voice mode we have been discussing). P25 data packets may be sent in either an unconfirmed mode, in which retransmission in the event of errors is handled by a higher layer of the protocol, or in confirmed mode, in which the destination radio must acknowledge successful reception of a data frame or request that it be retransmitted.

If the Unit Link IDs used by a target group are already known to an adversary, she may periodically direct intentionally corrupted data frames to each member of the

group. Only the header CRCs need check cleanly for a data frame to be replied to – the rest of the packet can be (intentionally) corrupt. Upon receiving a corrupt data transmission directed to it, the target radio will immediately reply over the air with a retransmission request. (It is unlikely that such corrupted data frames will be noticed, especially since the corrupt frames are rejected before being passed to the higher layers in the radio’s software responsible for performing decryption and displaying messages on the user interface). The reply transmission thus acts as an oracle for the target radio that not only confirms its presence, but that can be used for direction finding to identify its precise location.

While we are unaware of any P25 implementations that refuse to respond to a data frame that is not properly encrypted, even if encryption is enabled and a radio refuses to pass unencrypted frames to higher level firmware, the attacker may easily construct a forged but valid encryption auxiliary header simply by capturing legitimate traffic and inserting a stolen encryption header. This is possible because the protocol is optimized to recover from interference and transmission errors. Upon receiving a damaged packet – whether generated by an attacker or corrupted from natural causes – the target radio sends a message to request retransmission. This has the effect of allowing an active adversary to use the data protocol as an oracle for a given radio’s presence. It also allows an adversary to force a target radio to transmit on command, allowing direction finding on demand.

If the target radios’ Unit Link IDs are for some reason unknown to the attacker, she may straightforwardly attempt a “wardialing” attack in which she systematically guesses Unit Link IDs and sends out requests for replies, taking note of which ID numbers respond. However, in a trunked system or a system using Over the Air Rekeying, or in a system where members of the radio group occasionally transmit voice in the clear, Link IDs will be readily available without resorting to wardialing in this manner.

With this technique, an adversary can easily “turn the tables” on covert users of P25 mobile devices, effectively converting their radios into location tracking beacons.

3.4 Clear Traffic Always Accepted

All models of P25 radios of which we are aware will receive any traffic sent in the clear even when they are in encrypted mode. There is no configuration option to reject or mute clear traffic. While this may have some benefit to ensure interoperability in emergencies, it also means that a user who mistakenly places the “secure”



Figure 4: Motorola KVL3000 Keyloader with XTS5000 Radio

switch in the “clear” position is unlikely to detect the error.

Because it is difficult to determine that one is receiving an accidentally non-encrypted signal, messages from a user unintentionally transmitting in the clear will still be received by all group members (and anyone else eavesdropping on the frequency), who will have no indication that there is a problem unless they happen to be actively monitoring their receivers’ displays during the transmission.

Especially in light of the user interface issues discussed in Section 3.6, P25’s cleartext acceptance policy invites a practical scenario for cleartext to be sent without detection for extended periods. If some encrypted users accidentally set their radios for clear mode, the other users will still hear them. And as long as the (mistakenly) clear users have the correct keys, they will still hear their cohorts’ encrypted transmissions, even while their own radios continue transmitting in the clear.

3.5 Cumbersome Keying

The P25 key management model is based on centralized control. As noted above, in most secure P25 products (including Motorola’s), key material is loaded into radios either via a special key variable loader (that is physically attached by cable to the radio; see Figure 4) or through the OTAR protocol (via a KMF server on the radio network).

There is no provision for individual groups of users to create ad hoc keys for short term or emergency use when they find that some members of a group lack the key material held by the others. That is, there is no mechanism for peers to engage in public key negotiation among themselves over the air or for keys to be entered into radios by hand without the use of external keyloader hardware.

Thus there is no way for most users in the field to add a new member to the group or to recover if one user's radio is discovered to be missing the key during a sensitive operation. In systems that use automatic over-the-air keying at regular intervals, this can be especially problematic. If common keys get "out of sync" after some users have updated keys before others have, all users must revert to clear mode for the group to be able to communicate.⁴ As we will see in the next section, this is a common scenario in practice.

3.6 User Interface Ambiguities

P25 mobile radios are intended to support a range of government and public safety applications, many of which, such as covert law enforcement surveillance, require both a high degree of confidentiality as well as usability and reliability.

While a comprehensive analysis of the user interface and usability of P25 radios is beyond the scope of this paper, we found a number of usability deficiencies in the P25 equipment we examined.

As noted above, the security features of P25 radios assume a centrally-controlled key distribution infrastructure shared by all users in a system. Once cryptographic keys have been installed in the mobile radios, either by a manual key loading device or through OTAR, the radios are intended to be simple to operate in encrypted mode with little or no interaction from the user. Unfortunately, we found that the security features are often difficult to use reliably in practice.⁵

All currently produced P25 radios feature highly configurable user interfaces. Indeed, most vendors do not impose any standard user interface, but rather allow the

⁴This scenario is a sharp counterexample to the oft-repeated cryptographic folk wisdom (apparently believed as an article of faith by many end users) that frequently changing one's keys yields more security.

⁵In this section, we focus on examples drawn from Motorola's P25 product line. Motorola is a major vendor of P25 equipment in the United States and elsewhere, supplying P25 radios to the federal government as well as state and local agencies. Other vendors' radios have similar features; we use the Motorola products strictly for illustration. We performed some of our experiment with a small encrypted P25 network we set up in our laboratory, using a set of Motorola Model XTS5000 handheld radios.

radio's buttons, switches and "soft" menus to be customized by the customer. While this may seem an advantageous feature that allows each customer to configure its radios to best serve its application, the effect of this highly flexible design is that any given radio's user interface is virtually guaranteed to have poorly documented menus, submenus and button functions.

Because the radios are customized for each customer, the manuals are often confusing and incomplete when used side-by-side with an end-user's actual radio. For example, the Motorola XTS5000 handheld P25 radio's manual [14] consists of nearly 150 pages that describe dozens of possible configurations and optional features, with incomplete instructions on how to activate features and interpret displayed information that typically advise the user to check with their local radio technician to find out how a given feature or switch works. (Other manufacturers' radios have a similarly configurable design). That is, every customer must, in effect, produce a custom user manual that describes how to properly use the security features as they happen to have been configured.

In a typical configuration for the XTS5000, outbound encryption is controlled by a rotating switch located on the same stem as the channel selector knob. We found it to be easy to accidentally turn off encryption when switching channels. And other than a small symbol⁶ etched on this switch, there is little positive indication of whether or not the radio is operating in encrypted mode. Figure 5 shows the radio user interface in clear mode; Figure 6 shows the same radio in encrypted mode.

On the XTS portable radios, a flashing LED indicates the reception of encrypted traffic. However, the same LED serves multiple purposes. It glows steady to indicate transmit mode, "slow" flashes to indicate received cleartext traffic, a busy channel, or low battery, and "fast" flashes to indicate received encrypted traffic. We found it to be very difficult to distinguish reliably between received encrypted traffic and received unencrypted traffic. Also, the LED and the "secure" display icon are likely out of the operator's field of view when an earphone or speaker/microphone is used or if the radio is held up to the user's ear while listening (or mouth when talking).

The Motorola P25 radios can be configured to give an audible warning of clear transmit or receive in the form of a "beep" tone sounded at the beginning of each outgoing or incoming transmission. But the same tone is used to indicate other radio events, including button presses, low battery, etc, and the tone is difficult to hear in noisy

⁶On Motorola radios, this symbol is a circle with a line through it, unaccompanied by any explanatory label. This is also the symbol used in many automobiles to indicate whether the air condition vents are open or closed.



Figure 5: XTS5000 in “Clear” Mode

environments.

In summary, it appears to be quite easy to accidentally transmit in the clear, and correspondingly difficult to determine whether an incoming message was encrypted or with what key.

3.7 Discussion

The range of weaknesses in the P25 protocols and implementations, taken individually, might represent only relatively small risks that can be effectively mitigated with careful radio configuration and user vigilance. But taken together, they interact in far more destructive ways.

For example, if users are accustomed to occasionally having keys be out of sync and must frequently switch to clear mode, the risk that a user’s radio will mistakenly remain in clear mode even when keys are available increases greatly.

More seriously, these vulnerabilities provide a large menu of options that increase the leverage for targeted active attacks that become far harder to defend against.

In the following sections, we describe practical attacks against P25 systems that exploit combinations of these protocol, implementation and usability weaknesses to extract sensitive information, deny service, or manipulate user behavior in encrypted P25 systems. We will also see that user and configuration errors that cause unintended cleartext transmission are very common in practice, even among highly sensitive users.

4 Denial of Service

Recall that P25 uses a narrowband modulation scheme designed to fit into channels compatible with the current

spectrum management practices for two-way land mobile radio. Unfortunately, although this was a basic design constraint, it not only denies P25 systems the jamming resistance of modern digital spread spectrum systems, it actually makes them *more* vulnerable to denial of service than the analog systems they replace. The P25 protocols also permit potent new forms of deliberate interference, such as *selective attacks* that induce security downgrades, a threat that is exacerbated by usability deficiencies in current P25 radios.

4.1 Jamming in Radio Systems

Jamming attacks, in which a receiver is prevented from successfully interpreting a signal by noise injected onto the over the air channel, are a long-known and widely studied problem in wireless systems.

In ordinary narrowband channelized analog FM systems, jamming and defending against jamming is a matter of straightforward analysis. The jammer succeeds when it overcomes the power level of the legitimate transmitter at the receiver. Otherwise the “capture effect”, a phenomenon whereby the stronger of two signals at or near the same frequency is the one demodulated by the receiver, permits the receiver to continue to understand the transmitted voice signal. An attacker may attempt to inject an intelligible signal or actual noise to prevent reception. In practice, an FM narrowband jammer will succeed reliably if it can deliver 3 to 6 dB more power to the receiver than the legitimate transmitter (to exceed the “capture ratio” of the system). Jamming in narrowband systems is thus for practical purposes a roughly equally balanced “arms race” between attacker



Figure 6: XTS5000 in “Encrypted” Mode

and defender. Whoever has the most power wins.⁷

In digital wireless systems, the jamming arms race is more complex, depending on the selected modulation scheme and protocol. Whether the advantage falls to the jammer or to the defender depends on the particular modulation scheme.

Spread spectrum systems [5], and especially direct sequence spread spectrum systems, can be made robust against jamming, either by the use of a secret spreading code or by more clever techniques described in [9, 1]. Without special information, a jamming transmitter must increase the noise floor not just on a single frequency channel, but rather across the entire band in use, at sufficient power to prevent reception. This requires far more power than the transmitter with which it seeks to interfere, and typically more aggregate power than an ordinary transmitter would be capable of. Modern spread spectrum systems such as those described in the references above can enjoy an average power advantage of 30dB or more over a jammer. That is, in a spread spectrum system operating over a sufficiently wide band, a jammer can be forced to deliver more than 30dB more aggregate power to the receiving station than the legitimate transmitter.

By contrast, in a narrow-band digital modulation scheme such as P25’s current C4FM mode (or the lower-bandwidth Phase 2 successors proposed for P25), jamming requires only the transmission of a signal at a level near that of the legitimate transmitter. Competing signals arriving at the receiver will prevent clean decoding

⁷As a practical matter, the analog jamming arms race is actually tipped slightly in favor of the *defender*, since the attacker generally also has to worry about being discovered (and then eliminated) with radio direction finding and other countermeasures. More power makes the jammer more effective, but also easier to locate.

of a transmitted symbol, effectively randomizing or setting the received symbol. [2] That is, C4FM modulation suffers from approximately the same inherent degree of susceptibility to jamming as narrowband FM – a jammer must simply deliver slightly more power to the receiver than the legitimate transmitter.

But, as we will see below, the situation is actually far more favorable to the jammer than analysis of its modulation scheme alone might suggest. In fact, the *aggregate* power level required to jam P25 traffic is actually much *lower* than that required to jam analog FM. This is because an adversary can disrupt P25 traffic very efficiently by targeting only specific small portions of frames to jam and turning off its transmitter at other times.

4.2 Reflexive Partial Frame Jamming

We found that the P25 protocols are vulnerable to highly efficient jamming attacks that exploit not only the narrowband modulation scheme, but also the structure of the transmitted messages.

Most P25 frames contain one or more small metadata subfields that are critical to the interpretation of the rest of the frame. For example, if the 4-bit Data Unit ID, present at the start of every frame, is not received correctly, receivers cannot determine whether it is a header, voice, packet or other frame type. This is not the only critical subfield in a frame, but it is illustrative for our purposes.

It is therefore unnecessary for an adversary to jam the entire transmitted data stream in order to prevent a receiver from receiving it. It is sufficient for an attacker to prevent the reception merely of those portions of a frame that are needed for the receiver to make sense of the rest

of the frame.

Unfortunately, the P25 frame encoding makes it particularly easy and efficient for a jammer to attack these subfields in isolation.

A P25 voice frame is 1728 bits in length. The entire *NID* subfield containing the NAC + DUID (and its error correction code) represents only 64 bits of these 1728 bits. Jamming just the 64 bit *NID* subfield effectively denies the receiver the ability to interpret the other 1664 bits of the frame, even if those bits are received unmolested. A jammer synchronized to attack just the *NID* subfield of voice transmission would need to operate at a duty cycle of only 3.7% during transmissions. Such a pulse lasts only about 1/100th of a second.

To efficiently jam particular frame subfields, a jammer must synchronize its transmissions so that it begins transmitting at or just before the first symbol of the targeted field is sent by the transmitter under attack, and end just after the last symbol of the field has been sent. At 4800 symbols per second, each symbol lasts just longer than 0.2ms. This may seem at first to require an impossibly high degree of timing synchronization. But the P25 framing scheme actually makes it quite straightforward for a jammer equipped with its own receiver to tightly synchronize to the target transmitter. Recall that each frame begins with an easily-recognized frame synchronization word, which the jammer can use to precisely trigger its interference so that it begins and ends at exactly the desired symbols.

By careful synchronization, a jammer that attacks only the *NID* subfield of voice traffic can reduce its overall energy output so that it effectively has *more than 14dB of average power advantage* over the legitimate transmitter.

It may be possible to improve the advantage to the jammer even more by careful analysis of the error correction codes used in particular subfields in order to reduce the number of bits in the subfield that have to be jammed. (We assumed conservatively above that the attacker must jam *every* bit of the 64 bit *NID* field in order to prevent correct reconstruction of at least one bit of the *NID* payload, which clearly can be improved upon). This would permit even lower transmission times and average emitted power. It is not necessary to fully obliterate a critical protocol, merely to reliably (though not necessarily perfectly) prevent its correct interpretation.

Properly synchronized, a P25 jamming system can operate at a very low duty cycle that not only saves energy at the jammer and makes its equipment smaller and less expensive, but also makes the existence of the attack difficult to diagnose and detect, and, if detected, require the use of specialized equipment to locate it. (Note that the

length of the jamming transmission is only about 10ms long, which is far shorter than the “oracle” transmissions discussed in Section 3.3.) Such a jamming system need only be relatively inexpensive, requires only a modest power supply, and is trivial to deploy in a portable configuration that carries little risk to the attacker, as described below.

We note that there is no analogous low-duty cycle jamming attack possible against the narrowband FM voice systems that P25 replaces.

4.3 Selective Jamming Attacks

An attacker need not attempt to jam every transmitted frame. The attacker can pick and choose which frames to attack in order to encourage the legitimate users to alter their behavior in particular ways.

For example, it is straightforward to monitor for a non-zero MI field in a header frame (indicating an encrypted transmission) and to selectively jam portions of subsequent frames, while leaving clear transmissions alone, in order to create the impression to the users of a radio network that, for unknown technical reasons, encryption has malfunctioned while clear transmission remains viable, thus inducing the users to downgrade to clear transmissions. If the users are already conditioned (through other weaknesses in P25) to unreliable cryptography, such an attack might be dismissed as routine. As we discuss in Section 5, it appears to be reasonable to expect that many such users are so conditioned.

As another possibility, an attacker could choose to attack only uplink messages on the control channel of a trunked P25 system, thus effectively denying use of the entire trunked network at an extremely low cost to the attacker.

In addition to the complexities of detecting and direction-finding an attack lasting mere hundredths or even thousandths of a second, adversaries can take steps to render their attacks less vulnerable to detection and more difficult for the operators of a radio network to prevent. For example, an attacker could choose to deploy multiple battery operated jamming devices in a metropolitan area, placing them in public locations to make tracing of the devices harder, or even surreptitiously attaching them to the vehicles of third parties such as taxis or delivery trucks to cause confusion, and to make the jammers harder to locate. Such devices may be made arbitrarily programmable, changing which of a group of devices is active at any one time or even taking commands over the air.



Figure 7: Girltech IMME, with modified firmware

4.4 Experimental Results

To confirm that low duty cycle subframe jamming is effective against standard P25 receiver implementations and to examine practical jammer architectures that might be employed by an adversary, we implemented a low-power subframe jammer for P25 traffic for testing in our laboratory environment.

Recent work has shown that inexpensive software programmable radios such as the Ettus USRP are capable of implementing the P25 protocols and acting as part of a P25 deployment [7]. Their versatility and the availability of open-source P25 software makes them attractive for reception, but round-trip delays between the receiver and transmitter make the platform less than ideal for subframe jamming.

Instead, we implemented our proof-of-concept selective jammer for P25 frames using the Texas Instruments CC1110 platform. The CC1110 chip combines a CC1101 radio with an 8051 microcontroller in a single system-on-chip package, allowing for faster reaction times than a USRP or other software radio could support. When jamming reflexively, packets are passed to the 8051 one byte at a time, allowing a filter to selectively jam transmissions only if the received header matches an intended target.

While any CC1110 board for the correct frequency range is sufficient, we used the *GirlTech IMME*, a commercial toy intended for pre-teen children to text message one another without cellular service. Presently priced at \$30 USD, the package includes a handheld unit and a USB adapter, either of which may be used with our P25 client (for an aggregate price of \$15 per jammer).

In order to facilitate rapid development, our CC1110 toolkit for P25 was divided into a Python-language client that communicates with native 8051 applications through an open-source debugger, the GoodFET. [8] Operations

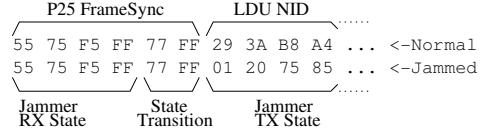


Figure 8: Sub-Frame Reflex Jamming

which do not require a fast reaction time are implemented only in Python, while timing-critical operations such as packet reception and sub-frame jamming are implemented as small fragments of C applications and are executed from RAM in the CC1110. Once a particular program has been verified to behave correctly, it can be rewritten as a stand-alone application to run from flash memory under battery power.

As shown in Figure 8, our sub-frame jammer is triggered by the LDU Frame Sync bitstream. Upon receiving this sequence, the CC1101 switches from its Receive to Transmit states. Starting the transition before the last 8 symbols of the 24-symbol Frame Sync are received allows the jammer-induced packet errors to begin from the very first byte of an LDU's NID field. Holding the transmission for the entire duration of the NID subframe and then ending it immediately produces an overall duty cycle of 3.7% relative to the transmitter under attack.

Our lab experiments were entirely successful. The GirlTech-based reflexive subframe jammer is able to reliably prevent reception from a nearby Motorola P25 transmitter as received by both a Motorola XTS2500 transceiver and Icom PCR-2500, with the jammer and the transmitter under attack both operating at similar power levels and with similar distance from the receiver. A standard off-the-shelf external RF amplifier would be all that is necessary to extend this experimental apparatus to real-world, long-range use. While we did not perform high power or long-range jamming ourselves (and there are significant regulatory barriers to such experiments), we expect that an attacker would face few technical difficulties scaling a jammer within the signal range of a typical metropolitan area.

5 Encryption Failure in Fielded Systems

Even if the P25 protocols and the design of P25 products might make them *potentially* vulnerable to user and configuration error, that does not automatically mean that fielded P25 systems are always insecure in practice. A natural question, then, is how successful the users of secure P25 radio systems are in preventing the unintended transmission of sensitive cleartext.

One way to answer this question might be through a usability study, such as the one seminally performed by Whitten and Tygar with PGP [19], in which researchers train test subjects to configure and use a P25 system and then observe their behavior and performance in a controlled environment. While such studies can have value in evaluating, e.g., different user interface designs from among a set of candidates, they have inherent limitations. Aside from the cost of recruiting and observing suitable test subjects, it can be difficult to replicate “real world” conditions – especially the motivation of the users to maintain security while getting their work done – sufficiently well to ensure that the results are representative of the system’s true usability under field conditions [3].

Instead, we measured and analyzed the incidence of unintended cleartext leakage in real P25 systems carrying a high volume of sensitive encrypted traffic with trained and motivated users: the secure tactical two-way radio systems used in federal criminal investigations.

An Over-the-Air Analysis

Although P25 is designed for general two-way radio use, the principal users of P25 in the US are law enforcement and public safety agencies. P25 has recently enjoyed particularly widespread adoption by the federal government for the tactical radios used for surveillance and other confidential operations by Federal law enforcement agencies such as the DEA, FBI, the Secret Service, ICE, and so on.

Most of the P25 tactical radio systems currently used by these agencies operate in one of two frequency bands in the VHF and UHF radio spectrum allocated exclusively for Federal use. There are approximately 2000 two-way radio voice channels in the Federal spectrum allocation (comprising 11 MHz in the VHF band plus 14 MHz in the UHF band, with channels spaced every 12.5 kHz). Most of these channels are unused in any given geographic area. The individual channels used by each given agency are assigned on a region-by-region basis, so a channel used by, say, the National Parks Service in one area might be used by the Bureau of Prisons in another area. Channels used for sensitive tactical law enforcement channels are mixed in among those of other Federal agencies and likewise vary on a regional basis. All Federal channel allocations are managed by the National Telecommunications and Information Administration and, unlike the state, local, and private frequency allocations managed by the Federal Communications Commission, are not published.⁸

⁸Although the Federal agency frequency assignments are not officially published by the government, some of the tactical frequencies

We built a P25 traffic interception system for the Federal frequency bands, which we operated over a two year period in two US metropolitan areas. Our system consists of an array of Icom PCR-2500 software-controlled radio receivers [11], an inexpensive (\$1000) wide-band receiver marketed to radio hobbyists and also popular in commercial monitoring applications. The PCR-2500 has several features that were important to us: relatively good performance in the federal VHF and UHF frequency bands, software programmability (via a USB interface), P25 capability via a daughterboard option, and the ability to search a range of frequencies to identify those in active use.

Our first task was to identify and catalog the particular frequencies used for sensitive tactical operations in each of our two metropolitan areas. We programmed PCR-2500 receivers located at two locations in or near each city to identify frequencies with P25 signals being transmitted in the federal frequency bands. We live monitored traffic on each identified frequency to determine whether it is used for law enforcement surveillance or other sensitive operations. After several months, we positively identified 114 frequencies in one city and 109 in the other as being used for sensitive law enforcement operations. While some of the frequencies we found carried a great deal of traffic, many others were only used sporadically. On every one of the sensitive frequencies we found, the traffic was predominantly encrypted, but still carried at least occasional cleartext. We could, of course, only monitor the transmissions that were sent in the clear (which extended the time required for our frequency cataloging process).⁹

We then set up infrastructure to intercept every cleartext transmission that occurred on the sensitive frequencies we identified. We dedicated a number of individual PCR-2500 receivers to intercept traffic on a few particularly active frequencies, in order to ensure that we would capture virtually all of the cleartext that was transmitted on them. (The frequencies with dedicated receivers were the output channels of nearby repeater systems, which had the desirable effect of ensuring that any transmis-

used by some agencies in some areas are relatively well known and can be found on the Internet. But most of the frequencies used for sensitive tactical communication are not published or widely known.

⁹It is explicitly legal under 18 USC 2511 for any person in the US to intercept and monitor unencrypted law enforcement radio traffic, even sensitive communication that perhaps *should* be encrypted. However, in the interest of public safety, we decline to identify here the particular frequencies used by particular agencies. Also, to comply with our institutional IRB requirements, we did not retain and will not disclose here any personally identifiable information we happened to monitor or derive, whether about surveillance targets or the government employees who were using the radios.

sions we did not record were not due to our receiver being out of geographic range but rather due to the traffic being encrypted). For the remaining frequencies, We used two additional PCR-2500 receiver in different locations around each city to continuously “scan” through the channels. and capture traffic detected during the scan (Icom supplies software that performs a similar function, but it did not have sufficient capability to record the P25 metadata we were concerned with, so we had to write our own software for this purpose). We operated this arrangement, on an increasing number of discovered frequencies and with an increasing number of receivers, over a period of two years.

We “live sampled” cleartext audio each day. We disregarded “non-sensitive” traffic such as radio tests or other messages for which encryption would be unnecessary or inappropriate (this represented only a small fraction of the traffic on the frequencies we were monitoring), leaving only “unintended” sensitive cleartext. We categorized each unintended cleartext message exchange according to the apparent error made or other reason it was sent in the clear. (We did not retain any identifying information about agents or targets).

In every case, sensitive traffic we sampled was sent in the clear under one of three scenarios:

- *Individual Error*: One or more users in the clear, but other users encrypted. In this scenario, all users clearly shared a common cryptographic key, since communication was able to occur unimpeded. But the users transmitting in the clear apparently accidentally switched their radios to transmit in the clear mode. Because the offending users still received the other users’ encrypted traffic and because those users had no way to reliably tell that they were sometimes getting clear traffic, this situation typically remained undetected.
- *Group Error*: All users operated in the clear, but gave an indication that they believed they were operating in encrypted mode. In some cases, this involved one user explaining to another how to set the radio to encrypted mode, but actually described the procedure for setting it to clear mode. In other cases, the users would simply announce that they had just rekeyed their radios to operated in encrypted mode (but were actually in the clear).
- *Keying Failure*: One or more users did not have the correct key, is unable to receive encrypted transmissions, and asks (in the clear) that everyone switch to clear mode for the duration of an operation so that all group members are able to participate.

Across all agencies, the unintended cleartext we intercepted was roughly evenly split among the *Individual Error*, *Group Error*, and *Keying Failure* categories. In general, we found that even when users knew they were operating in the clear (because they expressly indicated that they were switching to clear mode due to keying failure) and were engaged in sensitive operations, they made little effort to conceal the nature of their activity in their transmissions, and often appeared to “forget” that they were operating in the clear.

Note that every system we monitored had P25 encryption capability, and, indeed, most of the traffic sent was apparently successfully encrypted most of the time. Yet we still intercepted hundreds of hours of very sensitive traffic that was sent in the clear over the course of two years. While we will not identify here the agencies, locations, or particular operations involved, we note that the traffic we monitored routinely disclosed some of the most sensitive law enforcement information that the government holds, including:

- Names and locations of criminal investigative targets, including those involved in organized crime.
- Names and other identifying features of confidential informants.
- Descriptions and other characterizing features of undercover agents.
- Locations and description of surveillance operatives and their vehicles.
- Details about surveillance infrastructure being employed against particular targets (hidden cameras, aircraft, etc.).
- Information relayed by Title III wiretap plants.
- Plans for forthcoming arrests, raids and other confidential operations.

During March, April and May 2011, we intercepted a mean of 23 minutes of unintended sensitive cleartext per day per city across all monitored frequencies. Note that the variance was high; on some days, particularly weekends and holidays, we would capture less than one minute, while on others, we captured several hours. We monitored sensitive transmissions about operations by agents in *every* Federal law enforcement agency in the Department of Justice and the Department of Homeland Security. Most traffic was apparently related to criminal law enforcement, but some of the traffic was clearly

related to other sensitive operations, including counter-terrorism investigations and executive protection of high ranking officials.¹⁰

6 End-User Stopgap Mitigations

Many of the security problems in P25 arise from basic protocol design and architectural decisions that cannot be altered without a substantial, top-to-bottom redesign of the protocols and of the assumptions under which it operates. Given the critical and highly sensitive nature of much of the P25 user base, we strongly urge that a high priority be placed on such a redesign. However, until that occurs, there is little that the P25 user can do to defend against, e.g., the denial of service weaknesses we identified.

Other vulnerabilities arise from implementation errors or poor choices made by individual vendors (such as the transmission of unit IDs in the clear). These can be fixed without a redesign, but again, P25 users can do little to defend themselves here except to wait for the vendors to address these errors and deficiencies.

However, we note that there may be two areas in which P25 users and system administrators can immediately reduce the incidence of unintended sensitive cleartext transmission: improving the configurable of radio user interfaces and re-thinking their rekeying policies.

At least half of the unintended cleartext we captured was attributable to some form of “user error”. However, it would be a mistake to simply dismiss this as carelessness or to focus entirely on user awareness and training. In fact, these “user” errors are effectively *invited* by the radio user interfaces, and it is these interfaces to which we should assign the blame. But, fortunately, many current P25 radios can be “customer configured” by the end-user’s system manager to make the security state clearer to the user.

In particular, we suggest that the radios be configured *without* the use of the “secure” switch. Instead, encryption should be configured (“strapped”) to be always on (or always off) for each channel. Displayed channel names should be chosen to reflect whether encryption is strapped on or off, e.g., channel “TAC1” might be renamed instead to “TAC1 Secure” or “TAC1 Clear”. (If both secure and clear capability are required on the same frequency, the channel assignment can be duplicated).

¹⁰We are currently working with the agencies we monitored to help them improve their radio security practices. However, because many of the weaknesses that lead to cleartext leakage result from basic properties of the protocols and their implementations, incidents of unintended cleartext are likely to continue to occur from time to time even with increased user vigilance.

The second major cause of unintended cleartext that we captured arose from users who did not have current keys, often due to key expiration and the failure of the OTAR protocol. Some systems rekey weekly or monthly, and we found that users are inevitably left without current key material as a result.

We suggest that systems be configured to greatly minimize the required frequency of rekeying and to maintain keys for much longer than they are under current practice. Instead of monthly rekeys, systems should deploy long-lived, non-volatile keys that are changed only at very long intervals or if an actual compromise (such as a lost radio) is discovered. This will greatly improve the likelihood that users who wish to communicate securely will share common key material when they need it.

7 Conclusions

APCO P25 is a widely deployed protocol aimed at critical public safety, law enforcement, and national security applications. The user base for secure P25 is rapidly growing in the United States and other countries, especially among federal law enforcement and intelligence agencies that conduct surveillance and other covert activities against sophisticated adversaries.

As a wireless system, P25 is inherently vulnerable to passive traffic interception and active attack, and so it must rely entirely on cryptographic techniques for its optional security features. And yet we found the protocols and its implementations suffer from serious weaknesses that leak sensitive data, invite inadvertent clear transmission in “secure” mode, and permit active and passive tracking and traffic analysis. The protocol is difficult to use properly even when not under attack, as evidenced by our interception of large volumes of sensitive cleartext sent by mistake.

The protocol is particularly vulnerable to denial of service. Perhaps uniquely among modern digital voice radio systems, P25 can be effectively jammed with only a fraction of the aggregate signal power used by the legitimate user, by attackers with low cost equipment and without access to secrets such as keys or user-specific codes. Jamming attacks can also be used to aid in the exploitation of other weaknesses, such as selectively disabling security features to force users into the clear.

It is reasonable to wonder why this protocol, which was developed over many years and is used for sensitive and critical applications, is so difficult to use and so vulnerable to attack. We might compare P25 with other voice encryption protocols and systems, such as the US Government’s STU-III and STE [18] encrypting tele-

phone system used for classified traffic, that perform an ostensibly similar function and yet do not appear to suffer from such a large number of exploitable deficiencies. However, we note that P25 is based on a very different model from that of most cryptographic communication protocols. In the vast majority of cryptographic protocols, both sender and receiver are active participants in the protocol, and perform a negotiation or handshake before communication proceeds. In such protocols, both parties typically have the opportunity to discover and recover from errors, or abort the transaction, before any data is transmitted. P25, however, while used in “two-way” radio systems, is essentially a unilateral broadcast system. All cryptographic decisions are made entirely by the sender, with the receiver only a passive recipient of whatever the sender has transmitted. Protocols for such broadcast-based encryption have not been as widely formally studied as other forms of secure communication (with the possible exception of encryption in direct-broadcast television systems), and may represent a rich and difficult class of problem worthy of more attention by our community. We explore this in more detail in reference [4].

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