Come toward the Light:

A Post Biblical Project in Luminal Navigation

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1. Objectives
The goal of this project is to design an indoor navigation system that uses the fluorescent lights in the building of its intended use as location information sources. It shall be demonstrated that a fluorescent light, with proper modifications to its ballast, can be modulated with location information by frequency shift keying (FSK) digital modulation scheme. A receiver system that can discriminatingly demodulate the location information signals of multiple fluorescent light fixtures will be constructed. The receiver will be designed to send the demodulated location information to a laptop computer with proper software that can generate instructions that guide the user of the device from Point A to Point B in the building.

2. History of the Fluorescent Light Communication and Its Use in Navigation Systems
The idea of using fluorescent light for communication has been an active area of research for the past few decades. In 2001, a team of researchers from MIT and Cambridge University successfully demonstrated with a working prototype that fluorescent light can transmit data either in digital or analog form with sufficient bandwidth, and ascertained the prospect of using this technology for practical applications. One of the demonstrations included the transmission of music from a fluorescent light. A fluorescent lamp was specially designed to modulate a song on its light. Shining the lamp on a receiver connected to an audio system made its speakers play the music.

In 2007, an enterprise called *Talking Lights* launched a line of products that implemented the fluorescent light communication technique. Their products are currently on the market. They include a patented fluorescent ballast/modulator, a PCMCIA receiver that attaches to a personal computer as a peripheral device, and receiver software that decodes modulated fluorescent lights. Called *Talking Light Location Beacon Ballast*, the specially designed ballast can serve as a location source by producing fluorescent light, modulated with the location information of the lamp. When a person holding the PCMCIA receiver approaches the lamp, the receiver detects the modulated light, decodes the location information conveyed in the light, and relays this information to the person's computer. The company describes their technology as a type of wireless local area network (LAN) that establish communication link through fluorescent light.

3. Applications of the Fluorescent Light Navigation System.
The fluorescent light navigation system can be used for:
    a. Supporting people with brain injury or dementias that lack spatial cognizance in hospitals.
    b. Providing dynamic map information and location determination in museums.

The fluorescent light modulation can also be used to create a wireless mesh network for:
    a. Transmitting announcements/alerts to various parts of a building in case of emergency.
    b. Communication between two locations within a building.

4. Advantages over Conventional Wireless Network.
The wireless network that uses fluorescent lights as location sources offers several advantages over the wireless network that uses radio frequencies:

a. It's cheap. Most buildings today are already equipped with fluorescent light infrastructure. Retrofitting these buildings with the specially modified ballasts does not entail any significant cost.
b. The installation of the network is easy. It can be as simple as changing the ballasts of the lamps in the building, and distributing proper receiver devices to those in need of the technology.
c. It consumes less power. Each fluorescent light is a location information transmitter, and the power used for transmission is simply the power needed to keep the light on.
d. It is ideal for indoor navigation systems. Fluorescent lights are found in almost every part of a building. The receiver and the light fixtures on the ceiling are most likely to be in each other's line of sight time and again. Unless an action that blocks the light from the receiver is performed purposefully, the communication link between the lights and the receiver will not be interrupted as the receiver is moved around the building. On the contrary, navigation systems that use radio frequencies are more prone to communication failures because radio waves tend to interact with various obstacles in the building and are susceptible electromagnetic interference.

5. How Is This Project Different from *Talking Lights*?
The *Talking Lights* uses the patented *Talking Light Location Beacon Ballast.* No detailed inner workings of this device have yet been released to the public, except that the device uses PCM digital modulation technique. This project is different from the *Talking Lights* in that:

a. The ballast uses the FSK digital modulation scheme.
b. The receiver uses a CDMA Approach to Identifying the lamp of the closest distance.

6. How It Works
Overview
A ballast is the component of fluorescent light fixtures that regulate the AC current flowing into the electrodes of the fluorescent bulb. The rate of flicker of the fluorescent light is approximately twice the AC current supplied by the ballast.

As all navigation systems do, the receiver system that provides the user with path-finding instruction needs some form of signals that can be captured from its surroundings and allows it to locate the user's current position on the map. In the fluorescent navigation system, the fluorescent light shall serve as this location information sources. This is achieved by using a new type of ballast, redesigned with an added functionality that allows it to produce light that is FSK-modulated with location information, which will be called "location ID" from this point on. More specifically, the ballast switches the AC current of the lamp rapidly between two discrete frequencies. This way, the ballast can produce light signals that flicker alternately at two different frequencies. This is equivalent to FSK-modulating the light signal.

Note that the ballast being discussed is special-purpose high-efficiency *electronic* ballast, which is capable of producing fluorescent light flickering at a much higher frequency than the conventional, inexpensive magnetic ballast.
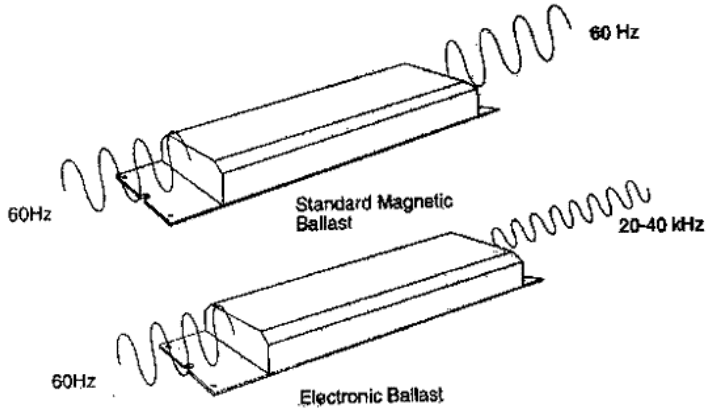
The navigation system is targeted for small-sized buildings where fluorescent lights are prevalent throughout each floor level, presumably installed on the ceilings of the building.

Each fluorescent lamp in the building shall be equipped with this newly modified ballast, and a unique location ID will be assigned to it. The location IDs of all the lamps shall form a mutually orthogonal set, so that the receiver may use them as CDMA signatures as part of its demodulation scheme.

Bird's Eye View of the Fluorescent Lights Layout on a Building Floor
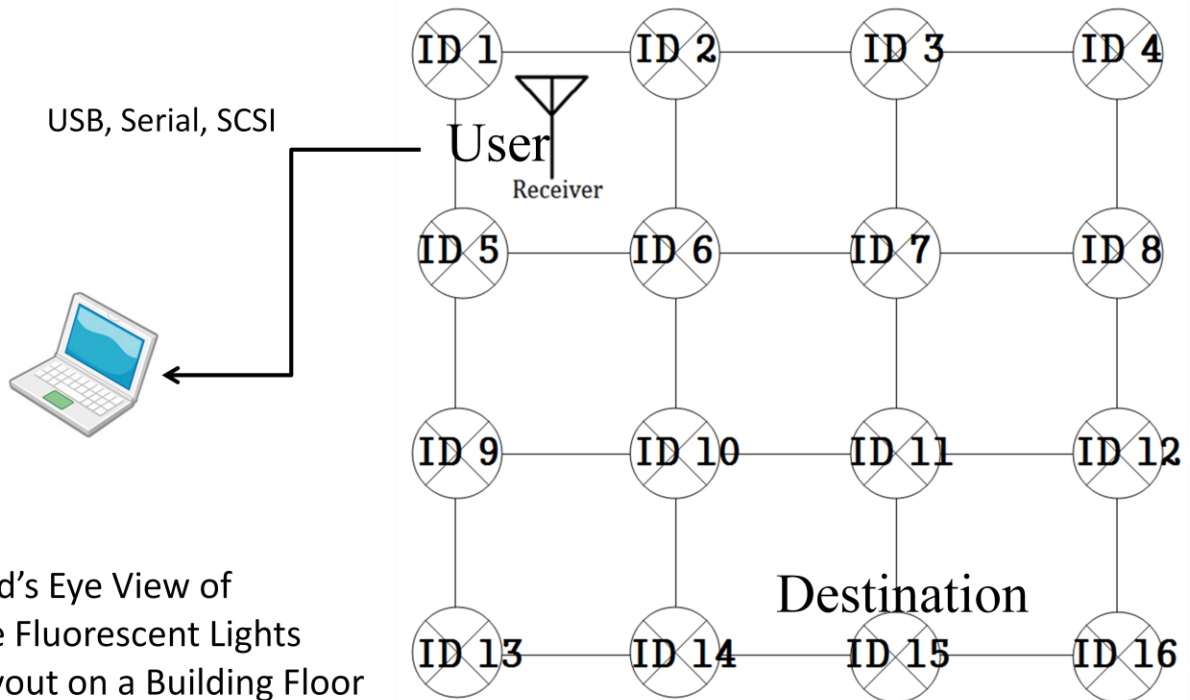
The ballast modulates the lamp with its unique location ID, and this location information is transmitted constantly to the light's surrounding whenever the light is turned on. When a person holding the receiver approaches any fluorescent-lit area in the building, the receiver perceives its location within the building by demodulating the location ID of the lamp closest to its position.
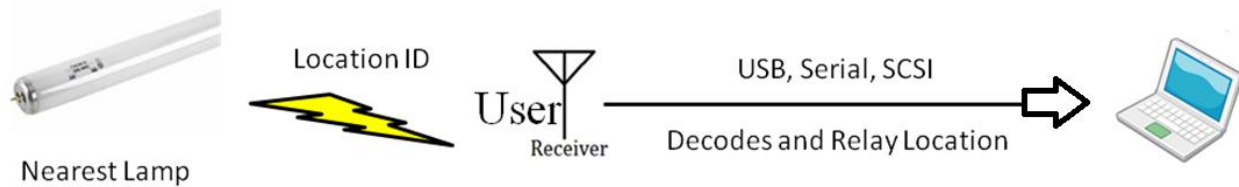
The receiver relays the location information to the laptop via a wire interface, and the software in the laptop calculates the optimal path for the user to his desired destination.

How the Fluorescent Light is Modulated by the Ballast
To obtain the ability to control the light's drive frequency, we must design and build our own ballast. This ability is not needed in existing commercial ballasts, and so such ability is not available in off-the-shelf parts. However, we can take a reference design, and modify it to suit our requirements, removing the most complex part of the design.

Because fluorescent lights operate at around 125 volts, and are powered from 110 volt (US) line power, there are safety concerns inherent in the execution of this project. By using a design as close to a known good reference, as well as taking common sense precautions, the risk of personal injury or equipment damage can be minimized.

Old style fluorescent lights use reactive ballasts to control the current entering the lamp, however the operating frequency of these is that of the line AC, and they are thus unsuitable for our project. Instead, we turn to high frequency, electronic ballasts.

High frequency ballasts are based on switched mode power supplies. These power supplies first convert the incoming AC to DC via a full wave rectifier, followed by a filter. The DC is then converted back to AC at a much higher frequency via a power oscillator, called a chopper, which can adjust its average output via PWM. A transformer isolates the output from the line power, and converts to the voltage we need. Finally, the chopper controller compares the output voltage to a reference value, and provides feedback to the chopper, stabilizing the output.
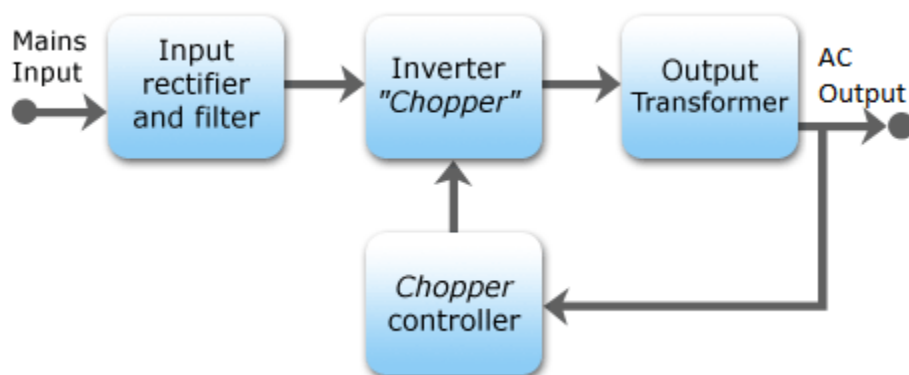
We are concerned only with the chopper, as it determines the drive frequency of the fluorescent light. In most commercial ballasts, the chopper is implemented with an IC called a PWM switch mode regulator. By finding one with an external frequency control, we can accomplish the modulation. An example is the National Semiconductor LM5002, its operating frequency is determined via a resistance, but it can also be synchronized with an incoming pulse sequence.

In our application, we are using a microcontroller of some variety to control the ballast. For ease of prototyping and programming, an Arduino is a strong candidate; however a cheaper, more limited one would bring down mass production costs. The microcontroller's function is to receive or store the message to transmit, as well as sending a signal to the PWM regulator.

Role of the Ballast

With the aforementioned modifications, the ballast can change the instantaneous frequency of the AC current it supplies to the electrodes of the fluorescent lamp. Then, the ballast can be used to FSK-modulate the flicker rate—and therefore the intensity—of the lamp light with its location ID. The location ID is a unique sequence of 0's and 1's that allows the receiver to identify the location of the lamp if demodulated successfully. An example of a lamp light modulated with a 4-bit location ID is provided below:
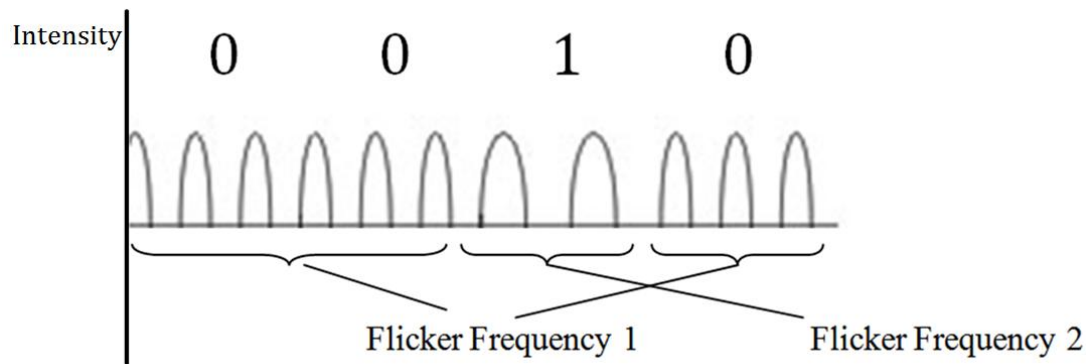

The above FSK modulated signal represents a location ID of 0010.

Demodulation of the Location ID Embedded FSK Light Signal by the Receiver

The receiver contains an omnidirectional photodiode that captures all modulated light signals from nearby fluorescent lamps. The diode is biased to operate in the photovoltaic mode, so that the diode becomes forward-biased only if a sufficient amount of light strikes the surface of the diode. Therefore, if a light signal that is FSK-modulated with a location ID is shone on the photodiode of the receiver, the voltage across the diode can be approximated as follows:
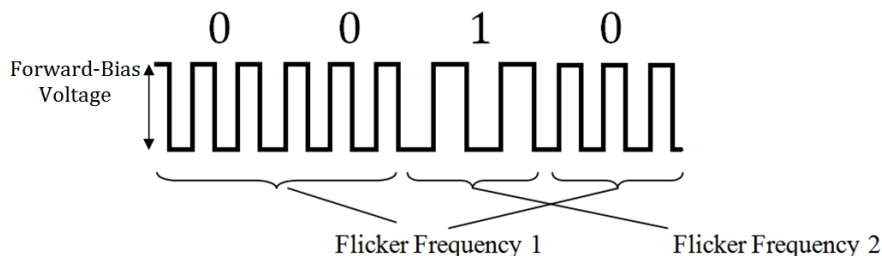
This is a square wave oscillating at two discrete frequencies. Using a phase-locked loop FSK demodulator with an appropriate loop bandwidth and lead-lag compensation, the receiver can recover the location ID encoded in the FSK signal.
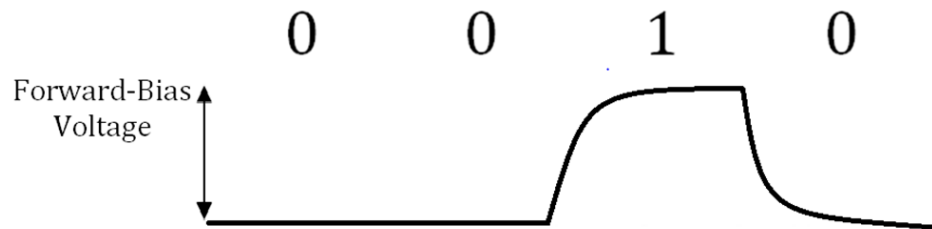
How does the receiver figure out which lamp it is currently closest to?
The light that reaches the receiver at an arbitrary fluorescent-lit location of the building is not that of a single lamp with a unique location ID. Most of the areas in the building are lit by a number of distinct fluorescent lamps. For geographically isolated areas, such as small classrooms, or restrooms, one central light fixture that is located at a vantage point that can reach all parts of the room well, only this light can be delegated to emit the location ID of the room as a whole. However, for hallways or large auditoriums more than one lights must be modulated with location information for the receiver to locate itself within different parts of this large area.

Suppose that all lights are modulated with a 4-bit location ID. The signal that the receiver actually sees is then the sum of the 4-bit location IDs from all nearby lamps of which light can reach the receiver. Therefore, the receiver must be capable of discriminating the light of the nearest lamp from all others, so that it can decode only the location information that most closely pinpoints its current position in the building.

The amplitude of each lamp's location ID is directly proportional to the intensity of the light from each lamp. Since the illuminance observed from the receiver is inversely proportional to the squared distance between the lamp and the receiver, the location ID of the lamp that is closest to the receiver will be the strongest signal component in the sum. In addition, for the attenuation rate of the light with distance is a square relationship, the contribution of the location ID of the lamps that are reasonably far from the receiver become quickly trivial with increasing distance.

Two different methods for the receiver to identify the lamp of the closest distance will be introduced, and their weakness and strengths will also be listed.

Method 1: Code Division of the Location IDs
The light from each lamp is modulated with a unique n-bit location ID. The number of bits required increases with the number of fluorescent lamps in the building that are to be used as location sources. In addition, the locations IDs are selected in such a way that they form a mutually orthogonal set.

The receiver has the location IDs of all the lamps preloaded in its memory. Using these location IDs as CDMA signatures, the receiver performs match-filtering; in other words, the receiver multiplies the received sum of location IDs with each CDMA signature and integrates this

product over a period. This is performed sequentially one location ID at a time, and each match-filtered output is stored in the receiver buffer. Note that the highest match-filtered output will be produced with the location ID of the closest lamp. Thus, at the completion of match-filtering, the receiver searches the buffer for the highest output and identifies the signature that produced this highest output. Since this signature is equal to the location ID of the closest lamp, the receiver can identify its current location in the building. A situation where the receiver must identify the nearest lamp among a pool of 4 lamps is presented below to illustrate the idea.
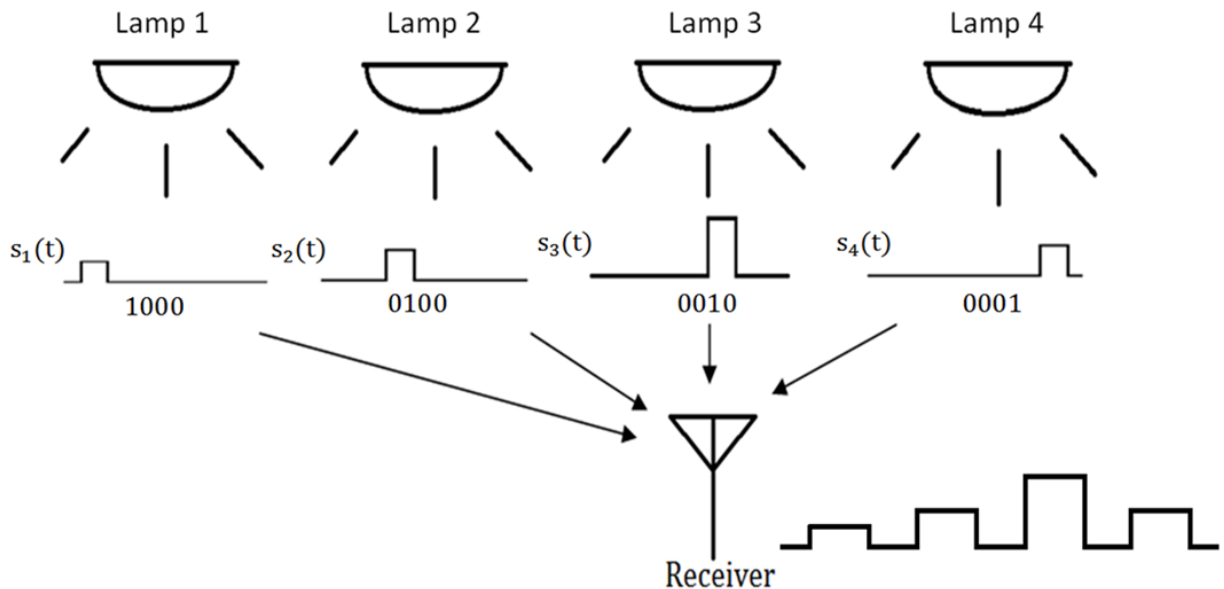

$$[s_1 + s_2 + s_3 + s_4]^T s_1$$

$$[s_1 + s_2 + s_3 + s_4]^T s_2$$

The receiver compares the match-filtered outputs and finds the maximum value, and the signature that produced this maximum.

$$[s_1 + s_2 + s_3 + s_4]^T s_3$$

$$[s_1 + s_2 + s_3 + s_4]^T s_4$$

A downside of Method 1 is that the location IDs emitted from the lamps must be synchronized with each other. If the bits of corresponding position in the location IDs do not occur in sync, the locations ID lose orthogonality, and the receiver may confuse the code for one lamp with that for another. Synchronization can be achieved by wiring all the fluorescent lamps to a central controlling station that can turn on all the lights at the same time. Periodically, all the lamps must be turned off and reset synchronously to eliminate any possible phase deviations that could have been introduced to the location ID signals of the lamp in the past cycle.

Method 2: Use Multiple Photodiode Detectors to Strengthen the Nearest Lamp's Signal
Instead of using a receiver with one photodiode detector, an array of tightly placed photodiodes can be used. The phases of the location ID signal from the nearest lamp that is at these diodes are almost identical, for their near-uniform distance from the lamp. The voltage signals across the

diode are first summed together, in order to make the location ID signal from the nearest lamp more pronounced. Then, the summed signal is passed through the PLL circuit for decoding. Finally, by using an ASK decision maker with appropriate DC reference voltage, the location ID signals of all the other lamps can be trimmed out.
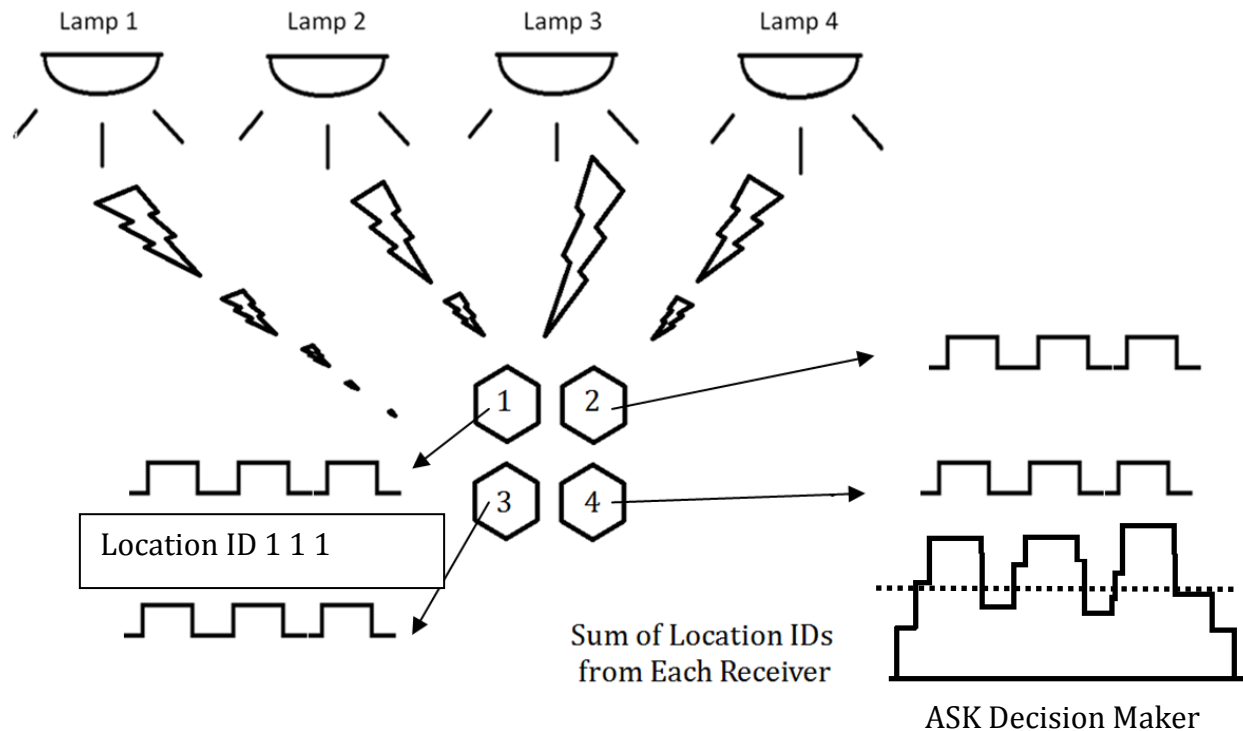
Method 2 offers a significant advantage over Method 1 in that the overhead of having to connect all the location source lamps in the building to a central station is reduced. The phase differences between the location ID signals from the lamps are no more a problem for the receiver because the receiver can pick out the location ID of only the nearest lamp without relying on code division. In addition, the location IDs of the lamps do not have be mutually orthogonal to each other. They just need to be unique. A slight disadvantage of Method 2 is that the complexity of the receiver circuit is increased because more photodiodes and PLLs are used.

Relaying the Demodulated Location ID to the Laptop Computer
The successfully demodulated location information from the receiver is passed to the laptop via a USB interface. The software in the laptop uses this location information to provide the user with appropriate path guidance to the desired destination.

The Software and the Routing Algorithm
The purpose of this software is to recognize which light has the highest intensity, isolate the signal and let that light source represent the location of the person. You can imagine the plot of these light intensities would very closely resemble a bell curve. Imagine walking down a narrow hallway (such as those in CORE). As you distance yourself from one light source, its intensity starts to diminish, but the upcoming light source goes from low to high intensity. This continues in a cyclic manner (with the exception to rooms, as all light sources within rooms or large

chambers will only exhibit one LID). That is to say, the light *nearest* to the diode will have the highest intensity.

A microcontroller will be connected to an omni-directional photodiode, which will be exposed to all light sources within an average of 25 feet. This microcontroller will act as a receiver, and will be connected to a device (laptop, handheld controller, etc.) via Serial or USB. We will most likely implement this receiver using the Arduino, as the freedom of customization fits our needs perfectly, and that the data, for initial test purposes, is to be uploaded via serial connection onto a terminal. I assume the output would resemble a continuous loop of interleaved messages pertaining to the LID and the intensity corresponding to that light – this is due to the fact that all light sources are constantly transmitting their LIDs and the controller can only capture them one at a time. To achieve higher efficiency, modifications will need to be made to the **wiring.c** and **timer.c** modules (part of Arduino's main library) so that signals are not lost, and that the inputs are synced so that the controller does not become overburdened. As an extension to this, the receiver can also mount a wireless transmitter (Xbee shield) so that a physical connection need not be necessary. Of course, this would require the software to include a packet capture utility.

Output Reference:

ffxxxxxx:x

Floor Number
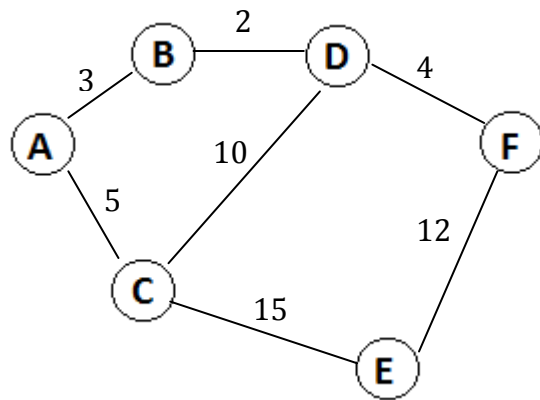Light Location Identifier
Intensity (floating point)

```
-- initially standing 2 feet away from Light 2 --
11000001 : 3.3
11000001 : 3.4
11000001 : 3.3
11000010 : 4.5
11000010 : 4.4
11000001 : 3.3
11000011 : 8.3
11000011 : 8.5
11000010 : 4.4
11000011 : 8.6
11000001 : 3.2
11000011 : 8.6
-- move 5 feet, now directly under Light 4 --
11000100 : 9.8
11000101 : 4.3
11000101 : 4.3
11000100 : 9.7
11000101 : 4.6
11000011 : 4.5
11000100 : 9.8
11000100 : 9.6
11000101 : 4.2
11000011 : 4.2
```

Light with the highest intensity represent the current location of the user. The intensities of the other LIDs will be seen as "noise" and ignored.

The output is interleaved, since all light sources are constantly transmitting their LIDs and the controller can only process them serially (think continuous loop).

When the light's Location Identifier is known, it will be compared with a list of values stored inside a database which points to its location on a map of the building (if the light codes need to be changed, the entire map does not need to be redesigned). The database may just be a text file corresponding the lights with the ID it transmits, and the map can be pre-installed or it can be acquired over the network. A background algorithm uses this location ID to find the shortest route to the destination – the shortest route is important as in the case of emergencies, as one must be able to navigate to the nearest exit when they do not know the structure of the building/floor. A graph traversal algorithm such as *Dijkstra's algorithm* solves this issue, as its main purpose is to find the shortest aggregate distance that needs to be traveled in order to arrive at a particular destination (in the fastest amount of time, where the "nodes" are in no particular order, and distances are strictly positive).

The algorithm starts at the initial light source (source node) and arrives at the destination light source (destination node) in a step-by-step manner, effectively building a shortest path in increments as it progresses. Each node in the graph is seen as a stop, and the distances between them (weighted edges) is seen as a step. From source to destination, there's an alternating sequence of steps and stops in between, and at each stop, the algorithm looks ahead (visit) to examine all the possible directions that are traversable. The smallest distance is visited, and then observes the distances from this node (and an already visited node is removed from the list so it is not revisited). This idea is applied to every subsequent node until the destination node is reached. Since the shortest path is taken upon every visit, the final path is almost surely going to be the shortest route. In a repetitive manner, the shortest distance is always taken. In this case, the problem of equidistant routes is also ignored, and the runtime is exclusively dependent on the total number of nodes that can be seen. Dijkstra's is also fairly quick in computation, even for a large number of light sources, so the wait/hang time would be negligible. The path will then be drawn so that the viewer can understand the building structure and feel comfortable with the route (and the path may or may not change if the person relocates). Below is a diagram (not drawn to scale) with a table of route calculations:

Step	Pick	D[B]	D[C]	D[D]	D[E]	D[F]
1	A (source)	3	5	∞	∞	∞
2	B		5	5	∞	∞
3	D		min(5,15)		30	9
4	C			15	15	∞
5	E					min(9,20)
6	F					

7. Demonstration of the Technology
The technology will be demonstrated by retrofitting an area on a single floor of the CORE building on the Busch campus with the fluorescent navigation system. The ballasts of the fluorescent lamps in the designated area will be replaced with the new electronic ballasts that are customized to perform FSK modulation. The area will be mapped out by assigning each fluorescent lamp with the new ballast a unique location ID. Then, two points in the area will be

selected, and the navigation system will be forced to guide a person holding the constructed receiver system from Point A to Point B.

8. Cost of the Project
The following table identifies electrical parts, equipments, and all other potential sources of expenses that are necessary to pursue the project from the initial conception to its demonstration.

Type of Expense	# Units Required	Price/Unit
PLL IC	Equal to the # of the photodiodes used in the receiver	Free
CDMA IC	Equal to the # of the fluorescent lamps to be converted to location sources	$2.00
Electronic Ballast	Equal to the # of the fluorescent lamps to be converted to location sources	$25.00
Microcontroller that relays location ID to the laptop via USB	Equal to the # of fluorescent lamps to be converted to location sources	< $30.00
Total:		~ $57.00